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Assessing seasonal drought variations and trends over Central Europe

Stephanie Hänsel[a,b,*], Zbigniew Ustrnul[c], Ewa Łupikasza[d], Petr Skalak[e]

[a] Deutscher Wetterdienst, Frankfurter Str. 135, 63067 Offenbach, Germany
[b] TU Bergakademie Freiberg, Interdisciplinary Environmental Research Center, Brennhausgasse 14, 09599 Freiberg, Germany
[c] Institute of Geography and Spatial Management, Jagiellonian University, Krakow, Poland
[d] Department of Climatology, University of Silesia in Katowice, Sosnowiec, Poland
[e] Global Change Research Centre AS CR, Brno, Czechia

A R T I C L E I N F O

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A B S T R A C T

The relevance of drought is still often underestimated for temperate climate regions like Central Europe that are characterized by on average ample precipitation. Nonetheless, several drought events in recent years (e.g. 1992, 2003, 2015 and 2018) demonstrated that droughts are a relevant factor for several economic activities (e.g., agriculture, water dependent industries, energy supply, etc.) in Central Europe. This is particularly true for the vegetation period, where increasing evapotranspiration rates due to rising atmospheric temperatures are intensifying existing drought conditions that originally developed from rainfalls deficits. The contribution of this study is an assessment of the long-term variability of drought conditions and seasonal climate trends within 1951–2015 based on a collective of 91 climate stations from the national meteorological services of Germany, Poland and the Czech Republic. Using a set of eight drought and three heavy precipitation indices an aggregated evaluation of seasonal precipitation characteristics is done and the driest seasons are identified for the entire study area as well as for four sub-regions. It is shown that the choice of the study period matters (1951–2015 vs. 1961–2015) as the pronounced (multi-)decadal variability of drought conditions restricts the temporal stability of computed trends. The drought trends computed for 1951–2015 are similar in direction, but generally smaller in magnitude than those of the ten year shorter period 1961–2015, as the 1950s have been a very dry decade in Central Europe. Seasonally, drying trends were observed for spring and less pronounced for summer, while autumn and winter show wetting trends. The seasonal trends are sensitive to shifts in the season definition by one month. Vegetation period I (VP-I) shows stronger drying trends, but less increases in heavy precipitation than spring, while the drought trends are less pronounced in vegetation period II (VP-II) as compared to the summer season, but more trends towards heavy precipitation increases occur in VP-II. These differences are explained by the daily trends in the seasonal cycle that show the strongest drying in April, June and the beginning of August and the strongest wetting in March and September. Generally, heavy precipitation increases prevail over decreasing trends in all seasons, whereby stations with strong drought trends generally have smaller positive or even negative heavy precipitation trends. A simultaneous occurrence of drought and heavy precipitation increases is observed in spring at several stations, particularly in sub-region West.

1. Introduction

The central European countries Germany, Poland and Czech Republic cover an area of nearly 750.000 km^2 with approximately 130 Million inhabitants. Several recent drought events demonstrated the relevance of drought for economic activities in Central Europe, an area that is climatologically characterized by relatively ample annual precipitation totals (e.g., compared to Southern Europe). Drought in Central Europe thus generally arises from a poor timing of rain (Trnka et al., 2016). Examples of recent severe meteorological drought events impacting the study area are the summer of 2003 (Rebetez et al., 2006), the period 2011/2012 (Zahradníček et al., 2015), the summer of 2015 (Hoy et al., 2017; Ionita et al., 2017) and the spring to summer season of 2018 (Imbery et al., 2018; Masante et al., 2018). Such meteorological droughts often propagate through the water system and develop into agricultural (soil moisture) and hydrological droughts. Reported impacts connected with these droughts include decreased streamflow or groundwater levels (Koehler et al., 2007; Kohn et al., 2014; Laaha et al., 2017), adverse effects on agriculture and forestry (Allen et al., 2010; Ciais et al., 2005; Hlavinka et al., 2009) and limitations in the energy production (De Bono et al., 2004; Fink et al., 2004).

* Corresponding author. Present address: Deutscher Wetterdienst, Frankfurter Str. 135, 63067 Offenbach, Germany.
E-mail address: stephanie.haensel@dwd.de (S. Hänsel).

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Different studies have explored the links between drought indices like the Standardized Precipitation Index SPI (McKee et al., 1993) and the Standardized Precipitation Evapotranspiration Index SPEI (Vicente-Serrano et al., 2010) and observed drought impacts on different systems (Stagge et al., 2015; Vicente-Serrano et al., 2012, Vicente-Serrano et al., 2013; Vicente-Serrano and Lopez-Moreno, 2005; Wang et al., 2014). They present a great variability in the times scales with the best correlation to drought impacts in dependence of the climate zone, the degree of human intervention, the geological and soil properties and the present vegetation (e.g. tree or crop species). Generally, the correlations between SPEI and drought impacts are slightly higher than those for the SPI (e.g., Bachmair et al., 2015; Vicente-Serrano et al., 2012; Wang et al., 2014). Stagge et al. (2015) describe for Europe the best correlations of SPEI to drought impacts at timescales of 2–3 months for rain-feed agriculture (with the highest sensitivity to drought stress during late spring and early summer) and at timescales of 9–12 months for agriculture that is more dependent on irrigation and water storage (snow, soils with high water holding capacity, groundwater). Variations of drought indices in winter are of low relevance for forests in Central Europe, as the soil moisture reservoirs are generally refilled before February (Mette et al., 2011). With respect to the water sector different timescales are relevant, depending on the catchment characteristics (López-Moreno et al., 2013; Lorenzo-Lacruz et al., 2013; McEvoy et al., 2012; Stagge et al., 2015). Drought impacts on public water supply and freshwater ecosystems are explained by a combination of short (1–3 month) and seasonal (6–12 month) anomalies of SPEI and SPI, respectively (Stagge et al., 2015). Thereby, for countries relying on surface water the correlations are highest at the timescale of 1 and 6 month, while for those relying on groundwater water the highest correlations are at the timescale of 3 and 9–12 months. Several studies furthermore indicated temporal changes in the relation between drought indices and impacts (Lorenzo-Lacruz et al., 2010; Vicente-Serrano and Lopez-Moreno, 2005). Bachmair et al. (2015) showed that drought impacts in the hydrological sector are often similarly well represented by the SPI as compared to streamflow percentiles.

The rising average earth surface temperatures and the related increase in water pressure deficit increasingly impact the observed severity of drought events, especially during the warm part of the year. This is related to the rising evaporative demand (Wang et al., 2012) that potentially increases drought frequency and severity (Dai, 2011; Vicente-Serrano et al., 2014b). The recent drought events were often accompanied by extremely high temperatures or long lasting heatwaves (Graczyk and Kundzewicz, 2014; Hoy et al., 2017; Rebetez et al., 2006; Sedlmeier et al., 2018). Nonetheless, summer drought in Central Europe is not a new phenomenon of the beginning of the 21th Century. Already the 1940s and the 1950s have been very dry (Briffa et al., 1994; Lloyd-Hughes and Saunders, 2002; Van der Schrier et al., 2006). During the summer half year of 1947 Central Europe was hit by an extraordinary drought event with wide ranging socio-economic consequences (Brazdil et al., 2016) and the drought events of the early 1950s were covering half of Europe at the time-scale of 12 months (Spinoni et al., 2015b).

At the European scale several drought studies have shown drying trends in Southern Europe, particularly in the Mediterranean region and wetting trends in Northern and North-Eastern Europe (Briffa et al., 2009; Gudmundsson and Seneviratne, 2015; Spinoni et al., 2017; Stagge et al., 2017), while the drought trends for central Europe are more diverse and often linked to temperature increases (Spinoni et al., 2015a). With regard to our study area Central Europe several drought studies address drought characteristics, observed and projected drought trends, causes of specific drought events and their impacts on different sectors in Germany (Hänsel, 2009; Huang et al., 2015, 2013; Lüttger and Feike, 2018; Schindler et al., 2007; Schwarzak et al., 2015), Poland (Łabędzki et al., 2014; Osuch et al., 2016; Radzka, 2015; Somorowska, 2016; Wibig, 2012) and the Czech Republic (Brazdil et al., 2015; Dubrovsky et al., 2009; Hlavinka et al., 2015; Potop et al., 2014; Potopová et al., 2018; Trnka et al., 2016, 2015; Zahradníček et al., 2016, 2015) or parts of these countries. Thereby, different drought indices and study periods were used, hampering the comparability of national study results as each index may capture a different part of the entire complex process of drought formation and propagation. Furthermore, some of these studies only addressed the drought characteristics and changes on an annual timescale, while others already pointed out that seasonal differences prevail in the precipitation trends over Central Europe.

This study aims at presenting a coherent picture of seasonal drought variability and trends over Central Europe for period 1951–2015. The novelty of our study is that it is the first comprising the three countries Germany, Poland and Czech Republic. The analyses are based on quality checked station data from three national meteorological services for a long study period of 65 years. Our contribution is an integrated assessment of the seasonal characteristics and trends of drought and heavy precipitation, while other studies often focus on the annual timescale or longer aggregation timescales and use different indices that restrict the comparability of individual study results. Furthermore, we focus on sub-regional drought anomalies and trends within Central Europe, a region that is generally considered as homogeneous (same climatological region) within larger scale European drought trend studies. Thereby, we support regional drought management decisions, as changes in the timing of precipitation within the year are relevant for example for management decision in the water and agricultural sector.

Different drought indices on daily and monthly timescales are used to assess drought intensity and duration. Some of these indices are purely precipitation based and others also integrate temperature in order to estimate water balance effects. Additionally, changes in heavy precipitation are evaluated in comparison to drought trends using three indices based on daily precipitation totals. In order to obtain an aggregated evaluation of drought and heavy precipitation the index values are standardized and integrated in aggregated evaluation indices. The temporal stability of trends is assessed by comparing the results to the ten years shorter study period of 1961–2015 and by applying a moving window trend analysis for 30 year periods. Furthermore, the dependence of analysis results on the definition of seasons is studied by shifting the spring and the summer season by one month and relating seasonal trends to daily trends of selected indices within the seasonal cycle. Within chapter 2 we are presenting the data base, indices and analysis methods used for our study. Chapter 3 illustrates the results with a focus on spatiotemporal drought characteristics, the dependence of results on the considered timescale and season, the temporal stability of trends and the changes in the seasonal cycle of temperature and precipitation. Within chapter 4 the results are discussed in the context of other studies. The main conclusions on the observed seasonal drought and heavy precipitation trends are presented in chapter 5.

2. Data and methods

2.1. Study area and data base

We are using daily time series of precipitation totals, average temperature as well as minimum and maximum temperature in order to evaluate the variability and change of drought conditions in Central Europe during 1951–2015. The analysis is based on data from 91 climate stations covering the countries Germany (44 stations), Czech Republic (16) and Poland (31; Fig. 1 and Table SM-1). This area is characterized by a temperate climate with influences of a milder oceanic climate in the West and a drier continental climate in the East. To account for this gradient the stations were grouped into four regions with similar precipitation characteristics (e.g. annual total and seasonal cycle) and trends. Those are the sub-regions West (W), Central (C) and East (E) as well as the Northern coastal area (N). Mountain stations are not considered separately but included in the analysis of the four defined regions, as there are only six station situated at an altitude above 1000 m (2 in W, 3 in C and 1 in E) and only 11 stations above 750 m.

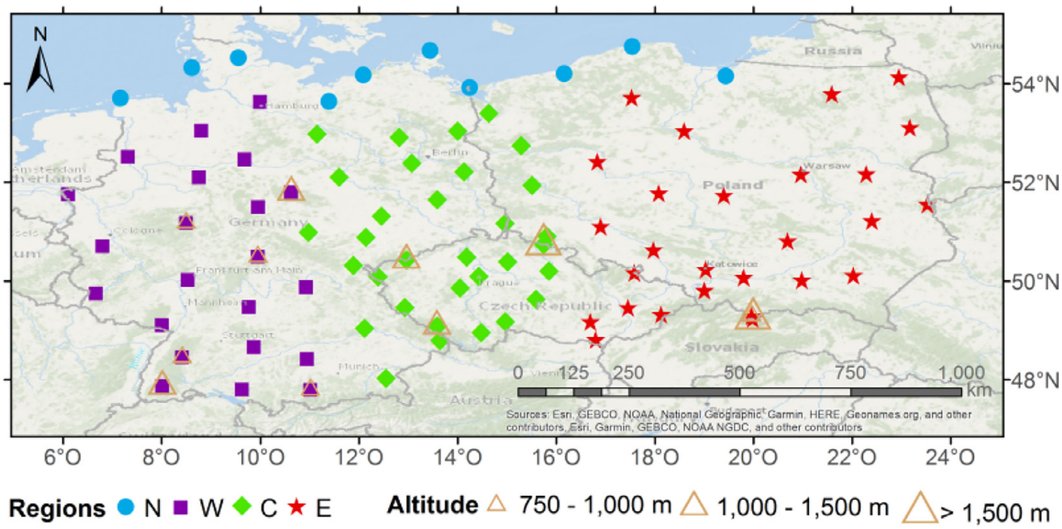


Fig. 1. Study area with regional classification of the climate stations (see Table SM-1) and indication of mountain stations > 750 m above sea level.

Table 1
Name, definition and units of the daily and monthly climate indices used in this study.

Index	Description	Unit
DD	Number of dry days (= days with daily precipitation totals below 1 mm)	d
AvD	Average duration of dry periods (= continuous sequence of dry days)	d
CDD	Consecutive dry days (= maximum duration of dry periods)	d
LPD	Number of low precipitation days (= days with daily precipitation totals below 5 mm)	d
AvL	Average duration of low precipitation periods (= continuous sequence of low precipitation days)	d
CLPD	Maximum duration of low precipitation days	d
MxRR	Maximum daily precipitation total	mm
R95pT	Precipitation fraction due to very wet days in percent (= precipitation total of days above the 95th percentile / total precipitation *100%)	%
R99pT	Precipitation fraction due to extremely wet days in percent (= precipitation total of days above the 99th percentile / total precipitation *100%)	%
mRAI	Modified Rainfall Anomaly Index (Hänsel et al., 2016; Van Rooy, 1965); Anomalies of precipitation at monthly timescales	without unit
WBAI	Water Balance Anomaly Index (Hänsel et al., 2016) Anomalies of the climatic water balance at monthly timescales	without unit
ADE	Aggregated Drought Evaluation index integrating the information of eight drought indices (DD, AvD, CDD, LPD, AvL, CLPD, mRAI, WBAI; for details see Section 2.3)	without unit
AHP	Averaged Heavy Precipitation anomalies of MxRR, R95pT and R99pT (arithmetic average of the relative anomalies of the respective indices)	%

The climate data stem from three national meteorological services. The German climate records are from Germany's national meteorological service Deutscher Wetterdienst (DWD) and freely available from the climate data center CDC.[1] The Polish time series originate from the archives of Institute of Meteorology and Water Management National Research Institute and were quality controlled by the authors. The time series of Czech climate stations originate from the Czech Hydrometeorological Institute. They were homogenized and checked for consistency using AnClim and ProClim software (Štěpánek et al., 2009).

Some of the time series have gaps of several days or months or start/end later/earlier than 1951/2015, but 70% of the time series have a data availability of > 99% (Table SM-1). All time series have a data availability of at least 75% for 1951–2016 and 85% for 1961–2015. Most of the Czech time series (13 out of 16 stations) only start in 1961 limiting the representativeness of analysis results for 1951–2016 over that territory. To account for the different start dates of time series the periods 1961–2015 and 1951–2015 are compared regarding the seasonal drought trends.

2.2. Drought indices

Precipitation characteristics are evaluated using indices based on daily as well as monthly data. We are also using a drought index incorporating information on evapotranspiration as the severity of drought may be underestimated by a purely precipitation-based index, particularly in a warming climate (Vicente-Serrano et al., 2010, 2014a). Thus, besides precipitation also temperature data are considered in order to estimate the potential evapotranspiration (PET) and to calculate the climatic water balance (WB).

Considered indices based on daily data are displayed in Table 1. Dry periods are defined as a sequence of consecutive day with precipitation below a specific threshold, whereby different studies use different thresholds like 0.1, 1.0, 5.0 and 10.0 mm/day (Cindrić et al., 2010; Lana et al., 2008; Perzyna, 1994; Serra et al., 2014). We use 1.0 mm/day for dry days and 5.0 mm/day for low precipitation days. Thereby, the threshold 1 mm/day is related to evapotranspiration processes and 5 mm/day to runoff-processes (Serra et al., 2014). The average and maximum duration of consecutive sequences of such days are studied. In order to compare the observed drought trends with changes in heavy precipitation three heavy precipitation indices are included in the analysis. We use the maximum daily precipitation total per season as an index for the absolute magnitude of heavy precipitation and two percentile based indices to capture changes in the precipitation fraction due to heavy precipitation days.

On a monthly basis and for the evaluation of drought conditions on longer aggregation time scales the Rainfall Anomaly Index RAI (Van Rooy, 1965) in a modified version mRAI (Hänsel et al., 2016) and the Water Balance Anomaly Index WBAI (Hänsel et al., 2016) are applied (Table 1). Hoy et al. (2017) have shown that the mRAI delivers well comparable results to the well-known Standardized Precipitation

[1] ftp://ftp-cdc.dwd.de/pub/CDC/observations_germany/climate/daily/kl/

Index SPI (McKee et al., 1993) over the middle latitudes of Europe, while the WBAI is comparable to the Standardized Precipitation Evaporation Index SPEI (Vicente-Serrano et al., 2010).

The indices mRAI and WBAI are calculated using a straightforward standardization approach for precipitation and the climatic water balance, respectively. The median precipitation total and water balance, respectively, is used as proxy for the average of the distribution, while the average of the five most extreme wet and dry cases describes the variability of the distribution. Different values representing the variability are used for each side of the distribution in order to account for skewed distributions. The mRAI of a certain month (or other aggregation period) i is calculated as follows:

$$mRAI_i = \pm SF * \frac{RR_i - \overline{RR}}{\bar{E} - \overline{RR}}$$

where

RR_i = Precipitation total of month i

$\overline{RR}$ = Median monthly precipitation of the base period 1961–2010 for the respective month

$\bar{E}$ = Mean of the 10 % most extreme precipitation totals of the base period 1961–2010 for the respective month. For negative anomalies of $RR_i - \overline{RR}$ the events below the 10th percentile are used and for positive anomalies those above the 90th percentile.

±SF = Scaling factor (positive for $RR_i \geq \overline{RR}$, and negative for $RR_i < \overline{RR}$)

A 50-year base period was chosen for the index calculations, as a long base period ensures a good representation of the climate variability and the extremes of the distribution. The period starting in 1961 was chosen, as data availability is best during these 50 years allowing for a regionally well comparable derivation of the factors needed to calculate the indices.

The calculation of the WBAI is done in the same way as illustrated for the mRAI by replacing precipitation with the water balance values.

$$WBAI_i = \pm SF * \frac{WB_i - \overline{WB}}{\bar{E} - \overline{WB}}$$

So the actual water balance value of month i (WB_i) is compared to the median value ($\overline{WB}$) of this month within 1961–2010 and the variability of the distribution is estimated by the distance of the mean of the 5 most extreme water balance values ($\bar{E}$) to the median of the distribution. For both calculations a scaling factor of SF = 1.7 is applied as suggested by Hänsel et al. (2016) in order to obtain similar values and class frequencies as those of SPI and SPEI. This allows using the same classification of moisture classes that were suggested by McKee et al. (1993) for the SPI (Table 2). The index values are classified in nine classes ranging from extremely wet to extremely dry conditions.

WBAI and mRAI are applied at timescales of 3, 6, 12 and 24 months. The respective timescale is indicated by a number in the index name, e.g. mRAI-12 refers to the modified Rainfall Anomaly Index at a timescale of 12 months. The different time-scales relate to different types of drought as the water deficit propagated through the hydrological system. Drought impacts on short-term water supplies that are important

Table 2
Classification of the mRAI and WBAI into nine moisture classes using the same classification suggested by McKee et al. (1993) for the SPI.

Class	Index-value	Description
1	≥2.00	Extremely wet
2	1.50 to 1.99	Very wet
3	1.00 to 1.49	Moderately wet
4	0.50 to 0.99	Slightly wet
5	−0.49 to 0.49	Near normal
6	−0.99 to −0.50	Slightly dry
7	−1.49 to −1.00	Moderately dry
8	−1.99 to −1.50	Very dry
9	≤ −2.00	Extremely dry

for agriculture are reflected by the timescale of 3 to 6 months, while longer aggregation periods refer to drought impacts on systems with a higher storage capacity and thus longer response times like streamflow, reservoir storage, and groundwater supplies.

Drought and wet periods are determined based on mRAI-12 and WBAI-12. A drought period starts if the index value drops below −1 and persists until the index values rise above zero. The respective wet period starts for index values above 1 and lasts until index values fall below zero. In order to describe the spatial extent of such a drought/wet period, the percentage of stations that is affected by drought/wet conditions is used as an approximation.

The Hargreaves-Samani approach (Hargreaves and Samani, 1985) is applied for the calculation of PET on a daily scale. It uses information on the geographical location, average precipitation totals and minimum as well as maximum daily temperatures. Thereby, minimum and maximum temperature is used to estimate solar radiation. The application of more complex PET calculation approaches like the Penman–Monteith formulation (Allen et al., 1998) is not possible due to the restricted availability of the necessary climate parameters (e.g., relative humidity, global radiation or wind speed). Nonetheless, several studies (Hargreaves and Allen, 2003; Mohammed and Scholz, 2017; Spinoni et al., 2017) have shown that the Hargreaves–Samani approach delivers well usable results that are closer to the reference PET computed by the Penman–Monteith formulation than those obtained with the Thornthwaite approach (Thornthwaite, 1948). The chosen Hargreaves–Samani approach was already successfully applied in other drought trend studies (Spinoni et al., 2017, 2018), as was the less suitable Thornthwaite approach (Briffa et al., 2009; Spinoni et al., 2015a,b). Stagge et al. (2014) have shown that the SPEI values are most sensitive to the chosen PET equation during spring and winter, while the best agreements were observed in summer.

2.3. Analysis approach

The indices are calculated for seasons (Spring: MAM, Summer: JJA, Autumn: SON, Winter: DJF). Additionally, two periods describing important agricultural vegetation periods are considered. These are the first or early vegetation period (VP-I: AMJ) and the second or late vegetation period (VP-II: JAS).

The drought indices (DI) are standardized using the same approach as applied for RAI and WBAI, so that the magnitude of index values and respective trends are well comparable. For deriving the standardized drought indices (SDI) this generalized formula is applied:

$$SDI_i = \pm SF * \frac{DI_i - \overline{DI}}{\bar{E} - \overline{DI}}$$

where

DI_i = Drought index month i

$\overline{DI}$ = Median drought index of the base period 1961–2010 for the respective month

$\bar{E}$ = Mean of the 10% most extreme drought index values of the base period 1961–2010 for the respective month. For negative anomalies of $DI_i - \overline{DI}$ the events below the 10th percentile are used and for positive anomalies those above the 90th percentile.

±SF = Scaling factor (positive for $DI \geq \overline{DI}$, and negative for $DI_i < \overline{DI}$)

The resulting standardized index values have the same range and can be easily averaged in order to obtain an aggregated evaluation of drought conditions. The Aggregated Drought Evaluation (ADE, Table 1) is computed by averaging mRAI, WBAI, the mean of the standardized versions of the three indices related to DD (DD, AvD, CDD) and the mean of the standardized versions of the three indices related to LPD (LPD, AvL, CLPD).

Applying the standardization approach described for the drought indices to the heavy precipitation indices resulted in some problems for the index R99pT, as there are too many years with zero precipitation due to events above the 99th percentile of each season. For an index mean

Table 3
Classification of trend values used for the illustration of the spatial consistence of seasonal trends (for index abbreviations please refer to Table 1).

Trend category	Description	Standardized drought indices	MxRR/ R95pT	R99pT	AHP
Very wet	Strong wetting trend	> 1.0	> 40%	> 70%	> 54%
Wet	Wetting trend	0.5 to 1.0	20 to 40%	35 to 70%	27 to 54%
Slightly wet	Slight wetting trend	0.25 to 0.5	10 to 20%	17 to 35%	13 to 27%
Indifferent	No trend	−0.25 to 0.25	−10 to 10%	−17 to 17%	−13 to 13%
Slightly dry	Slight drying trend	−0.5 to −0.25	−20 to −10%	−35 to −17%	−27 to −13%
Dry	Drying trend	−1.0 to −0.5	−40 to −20%	−70 to −35%	−54 to −27%
Very dry	Strong drying trend	< −1.0	< −40%	< −70%	< −54%

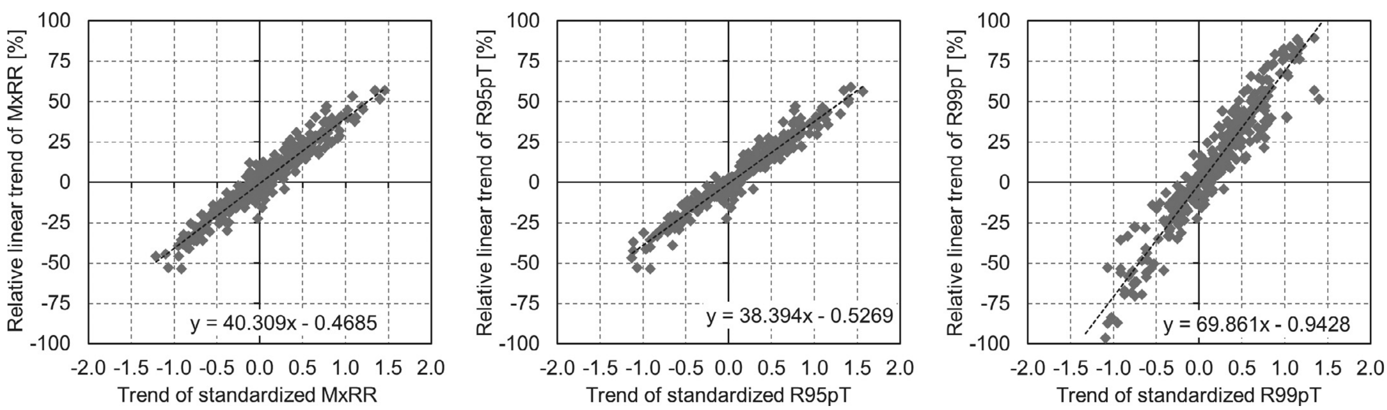


Fig. 2. Linear relationship between the relative linear trends and their respective counterparts for the standardized values of the indices MxRR, R95pT and R99pT.

of zero the standardization is not possible (division by zero). Furthermore, the simple standardization procedure does not work properly for distributions with a high skewness or a lower/upper bound close/equal to the average of the five lowest/highest values.

The trends are computed using linear regression. They are classified into seven categories according to trend magnitude (Table 3) for the illustration in trend maps and the comparison of individual indices in summarizing graphs of seasonal trends. The trend maps illustrate the spatial consistence of the seasonal trends, while the summarizing graphs allow for a straightforward comparison of different regions, seasons and indices.

In order to obtain well comparable trend classes for the relative trends of R95pT, R99pT and MxRR to those of the standardized drought indices a linear regression between the trends of the standardized and the non-standardized indices was applied for all seasons and all stations where the standardization was possible (Fig. 2). Additionally, we excluded very low (standardized index values <−2.0) and very high (>2.0) index values, as they often showed distinct deviations from the linear relationship. Based on the rounded values of the linear regression equation the thresholds of the drought classes in Table 3 were derived.

For an aggregated evaluation of heavy precipitation (AHP, Table 1) the relative anomalies of the three heavy precipitation indices were averaged. Based on the linear relationship (Fig. 3) between the seasonal trends for these relative anomalies and those for the standardized version of this index, thresholds for the drought classes for AHP were derived (Table 3).

3. Results

3.1. Spatiotemporal drought characteristics

Using relative indices shows that despite regional differences in the magnitude of average and extreme precipitation totals there are quite similar deviations from normal conditions over large parts of the study area during many years (Fig. 4a and b). A high percentage of stations

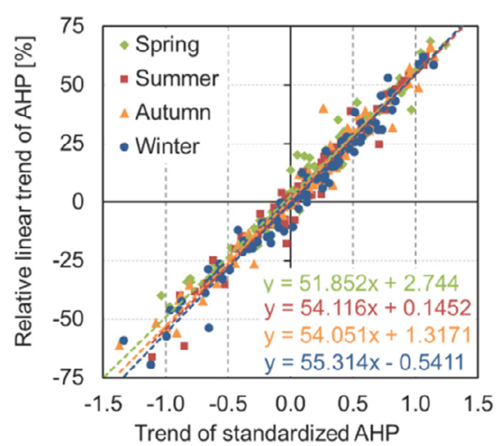


Fig. 3. Linear relationship between the relative linear seasonal AHP trends and their respective counterparts for the standardized AHP values.

with drought conditions (according to mRAI-12 and WBAI-12) occurred during 1953/54, 1959/60, 1962–65, 1971–74, 1976, 1982–84, 1990–92, 2003, 2015 (Fig. 4a–c; Fig. 6). During these phases different parts of the study area may be affected by drought conditions in different extent. For example, the drought period of 1953/54 has been particularly long and pronounced in the Eastern part of the study area, the one of 1982–84 affected mainly the Eastern and Central part, and another drought event in 1996/97 was most evident in the Northern and Western part.

Between 1951 and 1990 there has been a clear alternation between periods with predominantly wet and dry conditions over the study area, each of them reaching high spatial coverages (Fig. 4a–c). During the last 2–3 decades the pattern became patchier, meaning that the regional variability increased. This is also visible in the low pass filtered time series of spatial coverage (Fig. 4d), where since the mid-1990s the time series of wet and dry period coverage show a less pronounced peaks compared to the decades before.

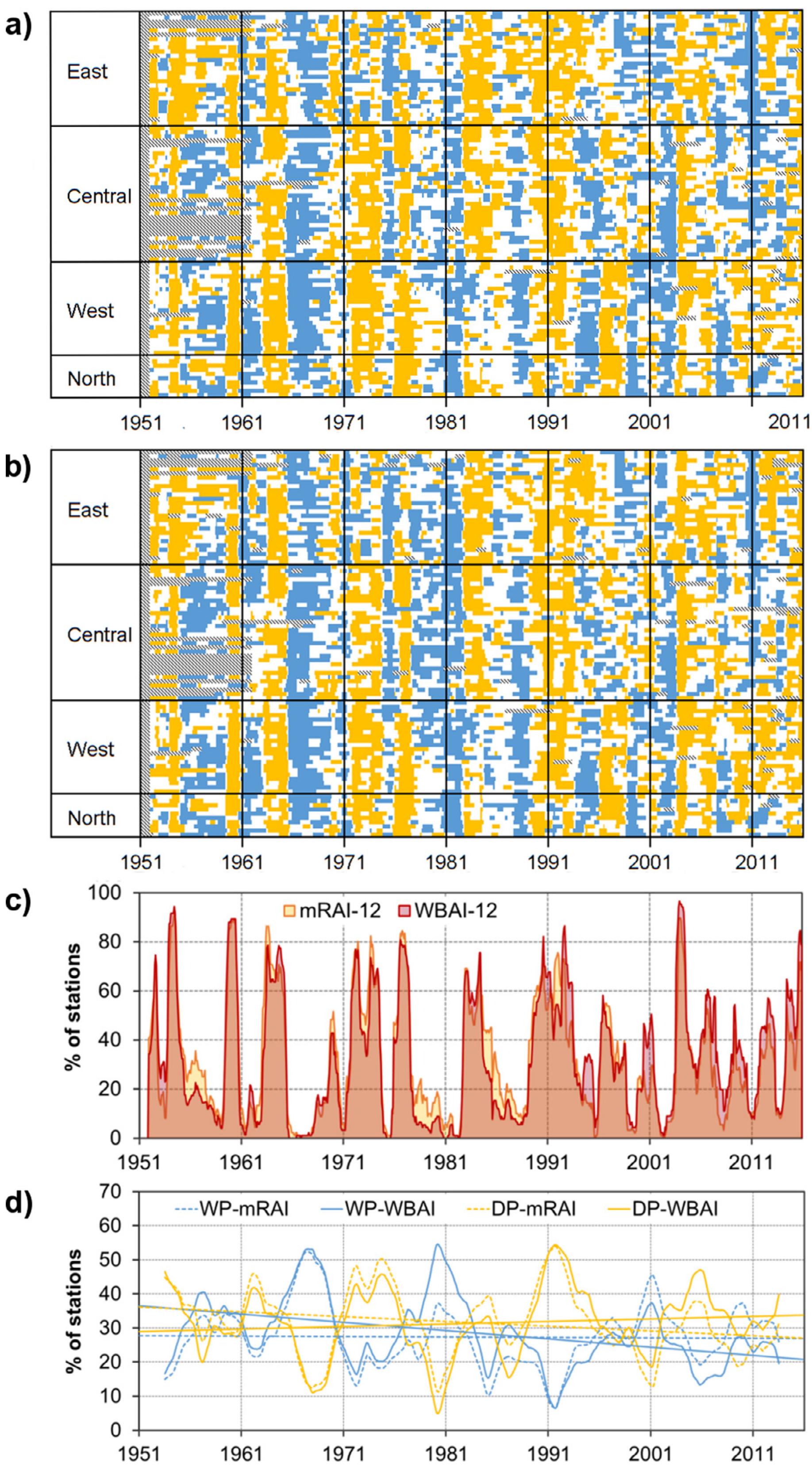


Fig. 4. Spatiotemporal drought pattern over the study area (each row represents one station; grey colors illustrate missing data) with dry (orange) and wet (blue) periods based on (a) rainfall data (mRAI-12) and (b) climatic water balance data (WBAI-12) in monthly resolution. Time series of the percentage of stations (c) under drought conditions comparing mRAI-12 and WBAI-12, and (d) under wet and drought conditions comparing mRAI-12 and WBAI-12 (60-month running average) including their respective linear trends for 1951–2015. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

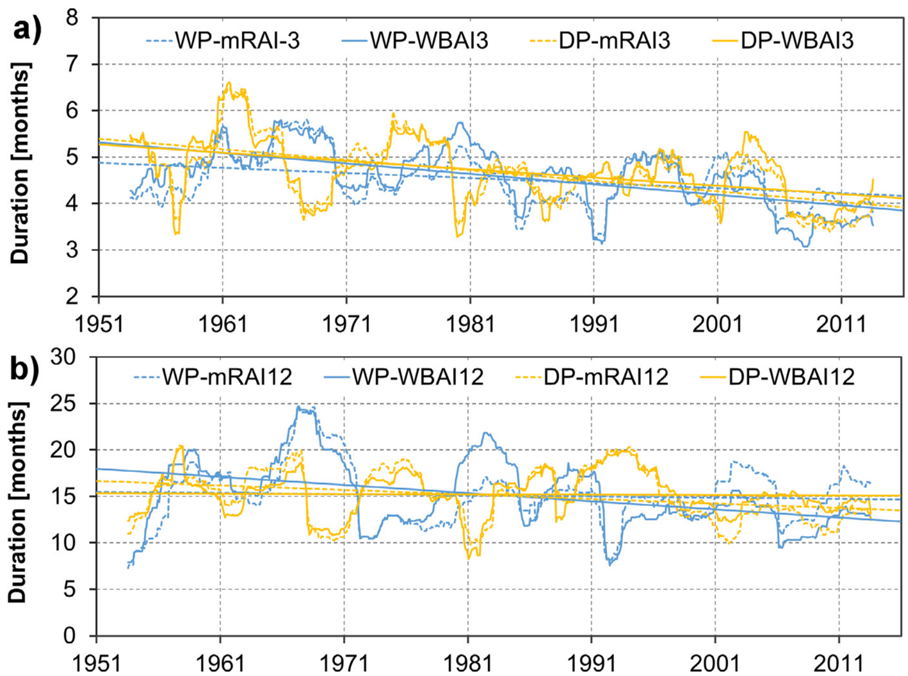


Fig. 5. Time series (60-month running average) of the duration of mRAI and WBAI dry (DP) and wet periods (WP) for the timescale of (a) 3 months and (b) 12 months. Displayed are also the respective linear trends for 1951–2015.

The analysis of drought periods (DP) and periods of sustained wet conditions (WP) for the indices mRAI and WBAI shows a decreasing duration for both, DP and WP, at the timescale of 3 months (Fig. 5a). The duration of dry and wet periods at the longer timescale of 12 months is decreasing for WBAI wet periods and mRAI dry periods over the study area, while there are no changes for WBAI dry periods and mRAI wet periods (Fig. 5b). The strong decrease of the duration of WBAI-12 wet periods matches the decrease in the spatial coverage of WBAI-12 WP. Averaged over the entire study area, the longest dry periods based on mRAI-3 and WBAI-3 occurred at the beginning of the 1960s and the longest wet periods between 1965 and 1969. The longest wet periods of mRAI and WBAI at the 12-month-timescale area occurred in 1967/68, while there are two DP of similarly long duration of mRAI-12 and WBAI-12, namely 1957 and 1992–94.

Figs. 4–6 also allow comparing the influence of the index definition on the depiction of spatiotemporal drought pattern and variations. The general pattern of the purely precipitation based index mRAI are very well comparable to those of the WBAI which includes information on temperature and evapotranspiration, respectively. Nonetheless, since about the 1990s the spatial coverage and duration of drought periods is in many cases higher for the WBAI as compared to the mRAI, while before 1990 percentage of drought affected stations was frequently higher for the precipitation based index mRAI. This observation is connected to the general temperature increase in the study area (Fig. 6d) and the accordingly increased evapotranspiration rates that may aggravate drought conditions caused by a rainfall deficit. Since the 1990s the difference between the WBAI-12 and the mRAI-12 is negative almost the entire time, while before the 1990s there were many phases with positive deviations (Fig. 6c). Thus drought conditions may be underestimated in recent times if a purely precipitation based index is applied.

The index selection also influences the drought trends, as the increasing evapotranspiration rates might offset or even overcompensate indistinct or slightly positive precipitation trends as well as enhance existing trends towards precipitation decreases (Fig. 4d). While the percentage of stations under drought conditions has decreased between 1951 and 2015 from 36% to 28% for the mRAI, it increased from about 30% to 35% for the WBAI. Similar is true for the wet periods, where no change in the percentage of wet period affected stations (around 27%) has been observed for the mRAI, but a distinct negative trend occurs for the WBAI (from 35% to 22%). Under consideration of the climatic water balance the average spatial coverage of drought periods has increased over the study area with a decreasing year to year variability and lower maximum values.

3.2. Drought characteristics at different timescales

The indices mRAI and WBAI have been calculated at different timescales between 1 and 24 months. These timescales are connected to different types of drought with the short timescales (e.g. 1 month) representing meteorological drought, the longer timescales of 3 to 6 months representing agricultural drought and the longest timescales of 12 and 24 months representing drought in hydrological systems under natural flow conditions. The longer the timescale the smoother the index time series and the longer the duration of dry and wet phases, respectively (Fig. 7). Displayed here, are only the time series of WBAI, as those of RAI show a similar temporal development (refer to Fig. 6 for the 12-month timescale). One event (1989–1993) sticks out by an unusually long duration, particularly at long timescales of 12 and 24 months representing hydrological drought conditions. Other events are characterized by a high magnitude of the regionally averaged drought intensity (e.g., 1953, 1959, 2002 and 2015).

Table 4 gives an overview on the five driest events at each timescale. Thereby only independent events have been considered. As there is a high autocorrelation of the index values at longer timescales, low index values tend to be followed by low ones. The five driest months occurred all between September and April and not during the summer months. This is probably connected to a larger spatial variability of precipitation over the study area during the summer months. Within smaller regions very low index values may be also reached during the summer months. Three of the driest months occurred after the year 2000, namely April 2007, November 2011 and March 2012, which is probably related to the increasing earth surface temperatures over the study area.

The driest 3-month periods ended between November and May. Some of these events comprise one of the driest months, e.g. Nov 1959 for WBAI-3 and Sep 1959 for WBAI-1, May/2012 for WBAI-3 and Mar/2012 for WBAI-1. Two of the five driest three month periods refer to the spring season (May 2011 and 2012) and thus strongly influence drought intensity trends of spring. Such drought events at timescales

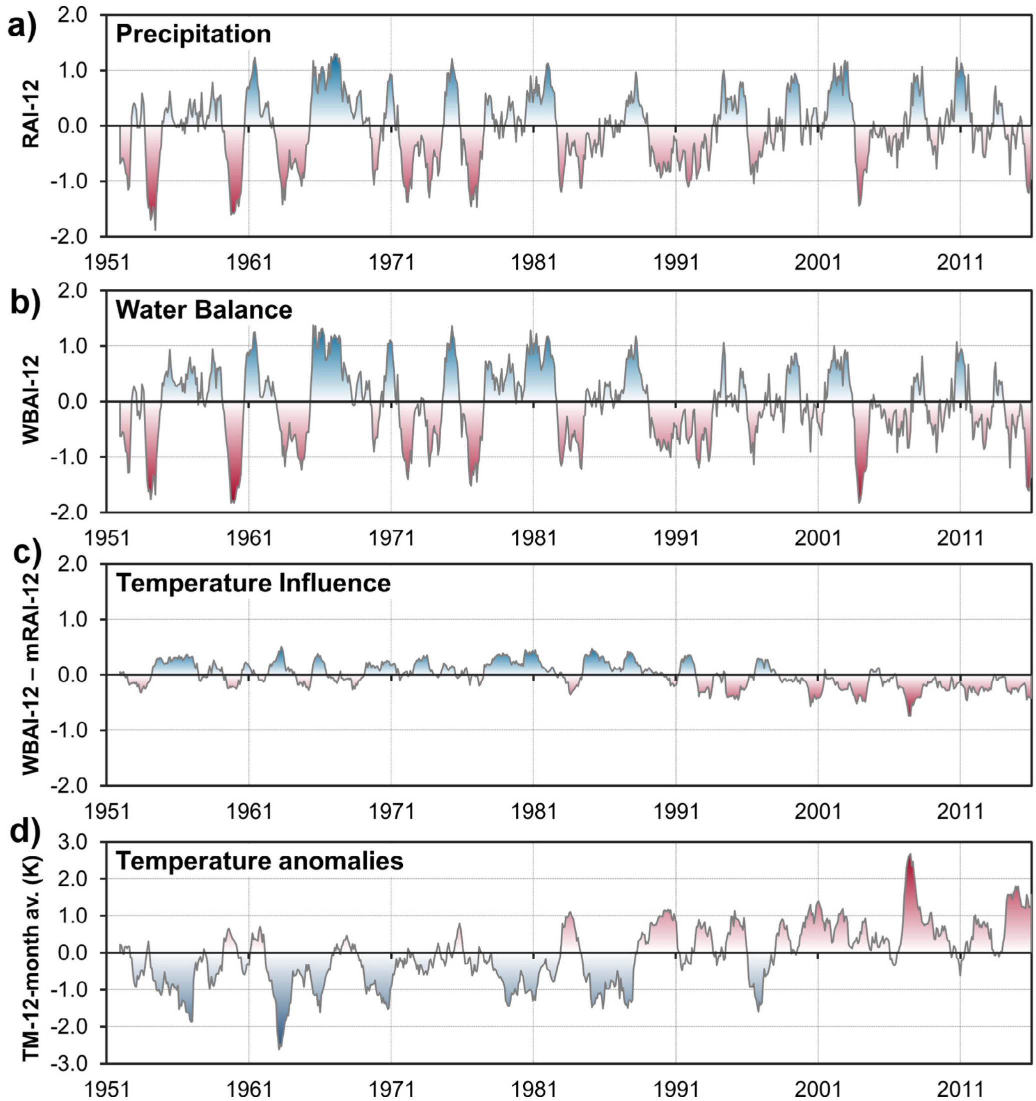


Fig. 6. Time series (average over the study area) of (a) RAI-12, (b) WBAI-12, (c) the difference between both indices indicating the influence of temperature on the drought evaluation and (d) the 12-month averaged anomalies of temperature.

Table 4
Five driest events (only temporally independent ones refereeing to different drought events) identified by the WBAI at different timescales (1, 3, 6, 12 and 24 months). Dependent months (such cases belonging to the same drought events) with index values below those of the fifth driest event are given in brackets. For timescales larger than one month only the last month of the calculation period is stated.

Rank	1 month	3 months	6 months	12 months	24 months
1	Nov 2011	Nov 1959 *(Oct)*	Feb 1954 *(Jan, Mar; Dec 1953)*	Oct 1959 *(Dec, Nov; Jan–Apr 1960)*	July 1964 *(Aug, Sep)*
2	Sep 1959	Dec 1953 *(Nov)*	Aug 2003 *(Jun, Sep)*	Nov 2003 *(Oct, Dec; Jan 2004)*	June 1960 *(May)*
3	Apr 2007	May 2011	July 1976	Feb 1954 *(Jan, Mar, Jun; Dec 1953)*	Oct 2015 *(Sep)*
4	Dec 1972	Mar 1972	Feb 1960	Oct 2015 *(Aug, Sep)*	Dec 1983 *(Jan 1984)*
5	Mar 2012	May 2012	Mar 1972	Aug 1976	March 1954

between 3 and 6 months affecting the vegetation period often have negative impacts on agricultural yields. At the timescale of six months Feb/1954, Aug/2003 and Jul/1976 have been the end months of the three driest periods. These periods are also represented by the driest events at the 12-month timescale, but at this timescale the periods ending in Oct/1959 and Nov/2003 have been even drier. At a timescale of 24-months several drought events at the beginning of the 1960s are cumulated leading to the most intense drought value for Jul/1964. Similar is true for the beginning of the 1980s, where the lowest WBAI-24 value is reached in Dec/1983. Such long drought events are often strongly affecting regional water supplies and are generally connected with low water levels in seas and reservoirs and low groundwater levels.

3.3. Seasonal characteristics and trends

The seasonal drought characteristics and trends are illustrated in Figs. 8 and 9 for the Aggregated Drought Evaluation (ADE) index. This index averages all eight drought indices considered in this study after applying the same standardization approach as used for mRAI and WBAI. More specific information and figures on individual indices are given in the supplementary material for each season (Supplement 1 to 4).

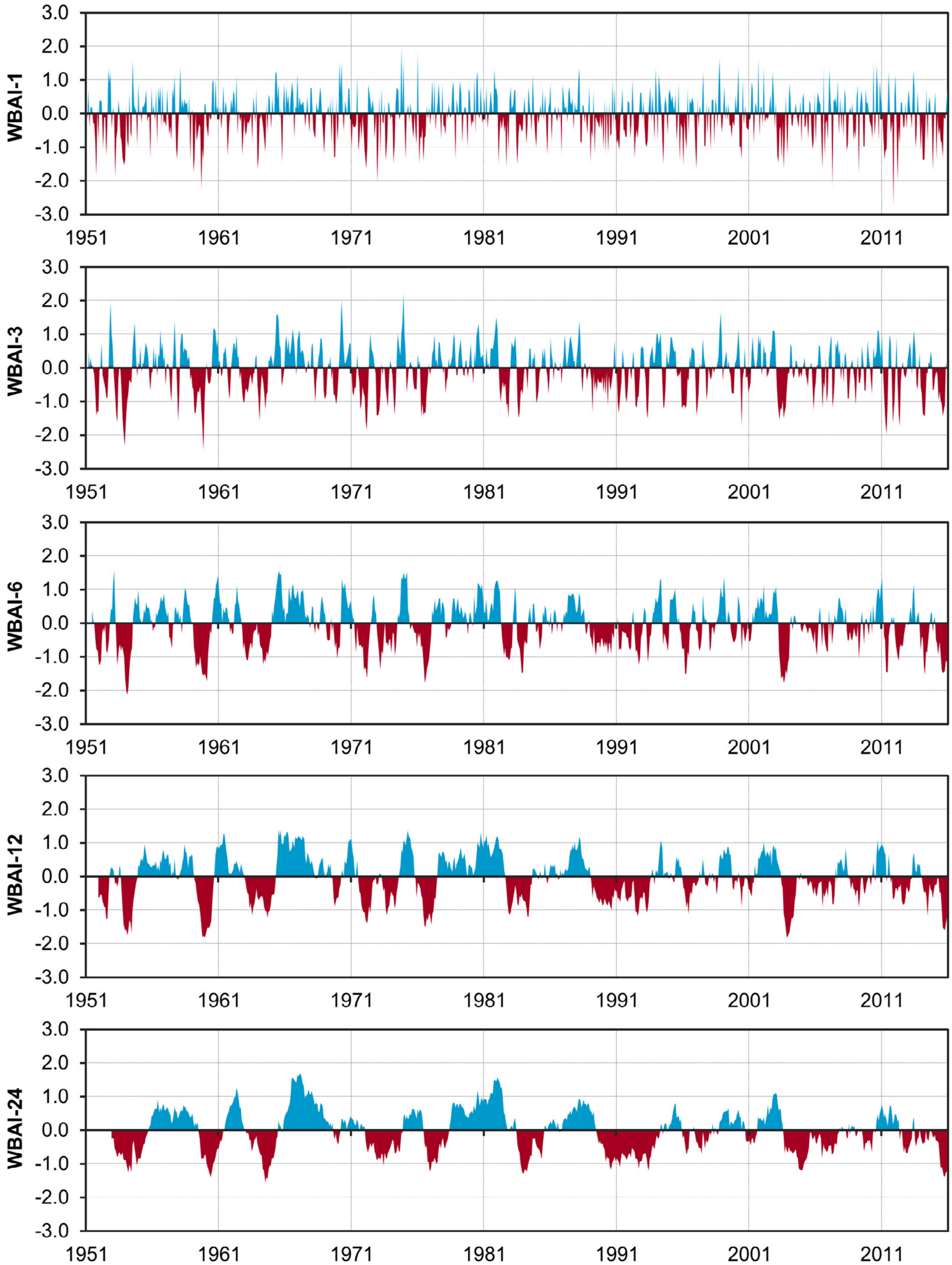


Fig. 7. Time series (regional average over the study area) of WBAI on different timescales (1, 3, 6, 12 and 24 months).

3.3.1. *Temporal drought variability*

The ADE time series show a strong year to year and decadal variability of drought conditions over the entire study area (Fig. 8). For instance, the 1950s were characterized by very dry spring seasons and very wet summers. Thus, computed seasonal trends strongly depend on the start year/decade. The 31-year moving averages of regional index values illustrate regional differences in the long-term variability of drought characteristics (Fig. 8). Often, the sub-region East behaves most different from the other regions. In all sub-regions, except for region East, the winters in recent decades were wetter than normal (regional 31-averages above zero). The recent spring seasons have been drier than normal (regional 31-averages below zero). For the summer season, the regional 31-averages decrease in the first half of the study period indicating a trend towards drier conditions. In the second half of the study period a slight increase towards wetter conditions (North) or stagnation (East) is visible. The regional 31-averages of ADE for autumn increase till the beginning of the 21st century and slightly decrease in recent years.

3.3.2. *Driest seasons*

The three driest seasons based on ADE over the entire study area and in each sub-region are summarized in Table 5. The driest winters have been 1963/64, 1972/73 and 1995/96, the driest springs occurred in 2011, 1953 and 1976, the driest summers in 1976, 1983 and 2003

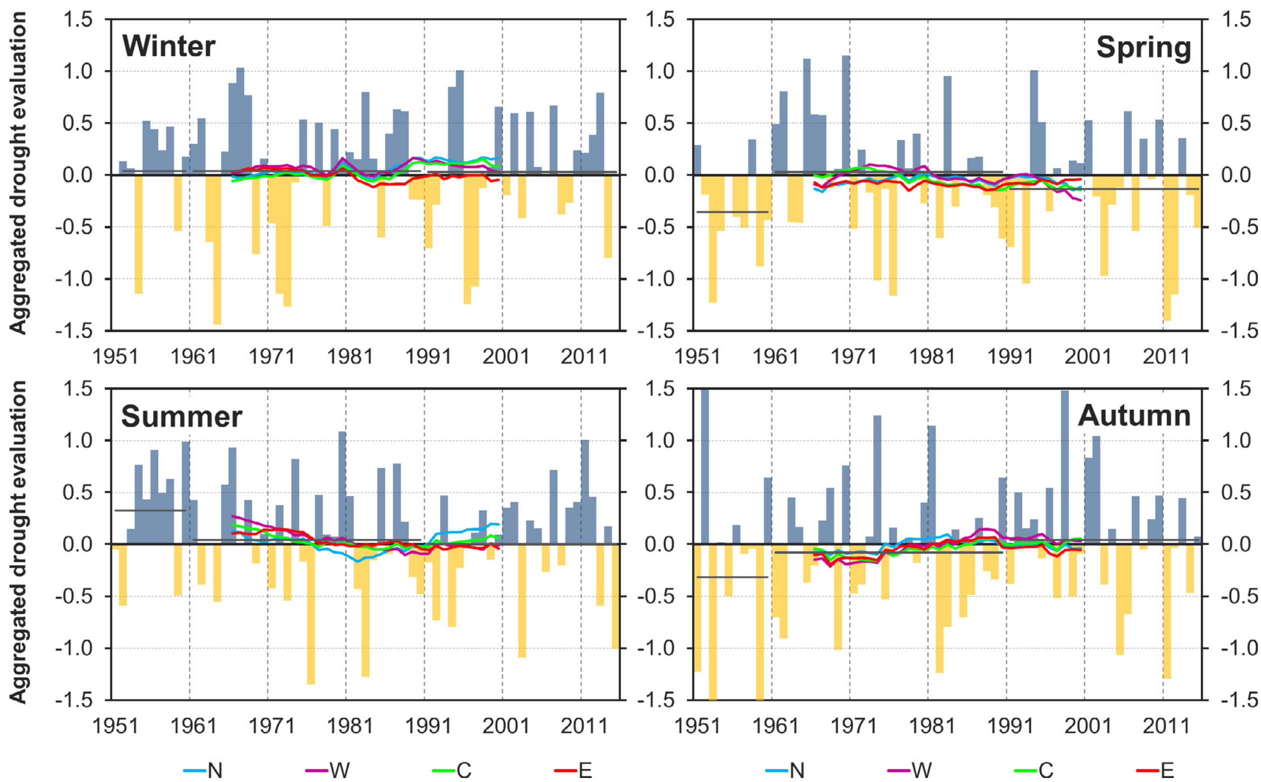


Fig. 8. Seasonal time series of the regionally averaged Aggregated Drought Evaluation ADE index. The grey lines indicate the averaged ADE values of 1951–1960, 1961–1990 and 1991–2015. The index values for the four sub-regions are displayed as 31-year moving averages.

Table 5
Three driest years per season and sub-region, as identified by ADE (Aggregated drought evaluation) that integrates all considered drought indices.

		Study area		North Coast		West		Central		East	
Season	Rank	ADE	Year	ADE	Year	ADE	Year	ADE	Year	ADE	Year
Winter	1	-1.4	1964	-1.6	1996	-1.7	1964	-1.6	1964	-1.5	1954
	2	-1.3	1973	-1.4	1964	-1.6	1972	-1.5	1973	-1.5	1997
	3	-1.2	1996	-1.3	1997	-1.5	1996	-1.2	2014	-1.0	1964
Spring	1	-1.4	2011	-1.8	1974	-2.1	2011	-1.4	2011	-1.3	1974
	2	-1.2	1953	-1.2	1960	-1.5	1976	-1.4	1953	-1.2	1953
	3	-1.2	1976	-1.2	2011	-1.4	1953	-1.4	1976	-1.1	2012
Summer	1	-1.4	1976	-1.6	1976	-1.7	1976	-1.5	1976	-1.6	2015
	2	-1.3	1983	-1.6	1983	-1.5	1983	-1.3	2003	-1.5	1992
	3	-1.1	2003	-1.3	1975	-1.4	2003	-1.2	1983	-1.4	1994
Autumn	1	-2.4	1959	-2.2	1959	-2.5	1959	-2.5	1959	-2.3	1959
	2	-1.6	1953	-1.5	1982	-1.7	1953	-1.8	1953	-1.9	1951
	3	-1.3	2011	-1.4	2011	-1.7	2011	-1.5	1982	-1.7	2011
VP-I	1	-1.3	1976	-1.4	1974	-1.6	1976	-1.5	1976	-1.1	2000
	2	-0.9	2003	-1.0	1959	-1.4	2011	-1.2	2003	-1.1	1976
	3	-0.8	2000	-1.0	1976	-1.0	2015	-1.0	1992	-0.9	1957
VP-II	1	-1.2	1983	-1.4	1983	-1.8	1959	-1.4	1971	-1.2	2015
	2	-1.1	1971	-1.3	1982	-1.3	2003	-1.1	1983	-1.1	1982
	3	-1.1	1959	-1.2	1976	-1.3	1991	-1.1	2003	-1.1	1983

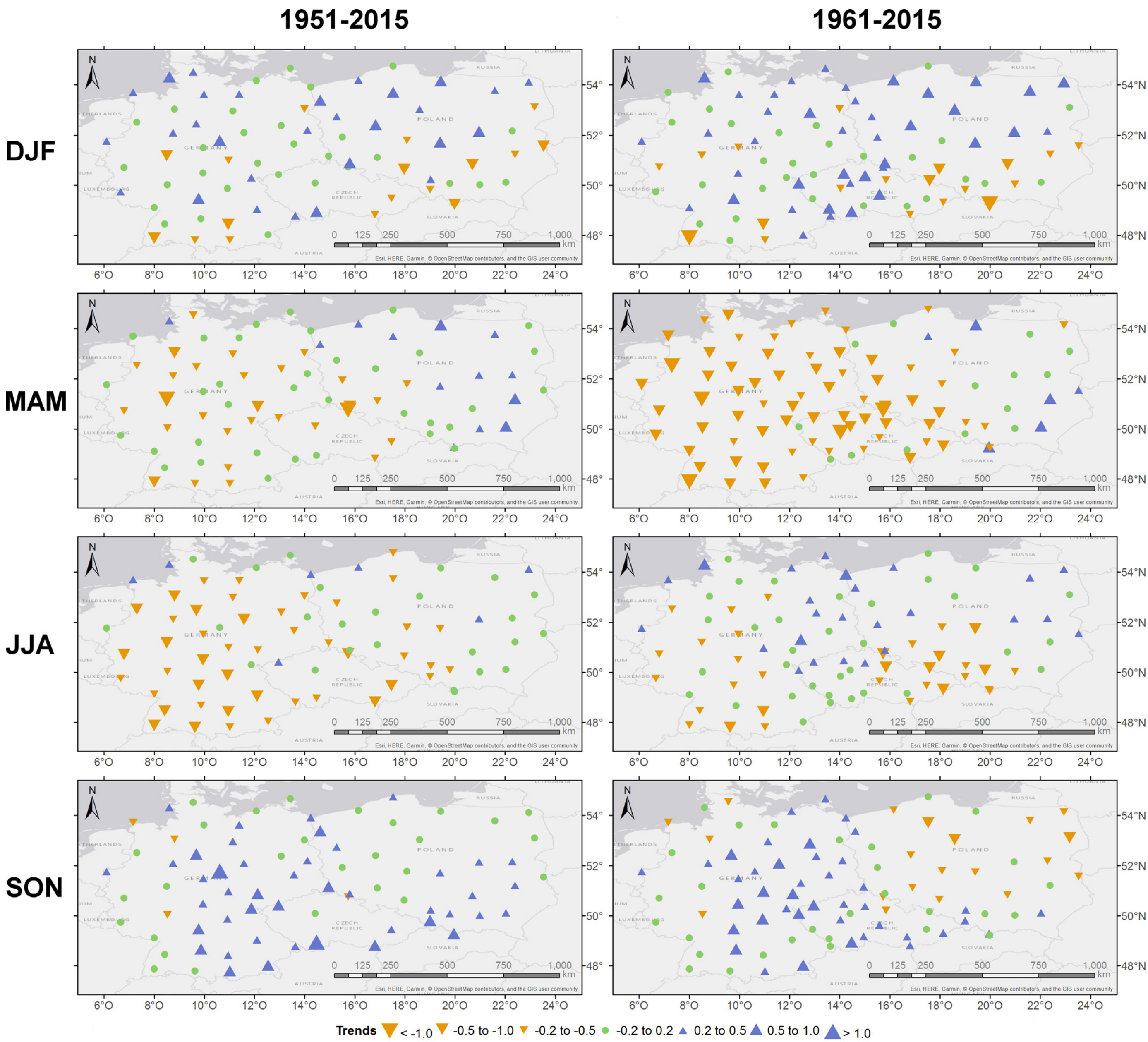


Fig. 9. Seasonal trends (linear regression) of ADE comparing the periods 1951–2015 and 1961–2015.

and the driest autumns in 1959, 1953 and 2011. The driest season for the entire study area also ranks under the TOP 3 events in almost all sub-regions. This fact indicates that these drought events have been spatially very widespread and probably cover neighboring countries. The strongest similarities between the TOP 3 years of the entire study area and those of the sub-regions occur for region Central. Here 2–3 of the three sub-regionally driest years per season are under the entire TOP 3. Region Central is situated in the middle of the study area and thus captures drought events whose spatial focus is more to the west and the east, respectively.

In 1953 and 2011 spring and autumn have been very dry, while the summer of 1953 had normal precipitation and the summer of 2011 was the second wettest in the ADE time series. In 1976 one of the driest springs was followed by the driest summer. This drought affected particularly the sub-regions West and Central, and during summer also sub-region North. The three driest summers in sub-region East, namely 2015, 1992 and 1994, are completely different from those of the other three sub-regions. The summers of 1983, 2003 and 1976 rank fourth, fifth and sixth driest summer in the ADE series of sub-region East, while 2015 was the fourth driest summer in sub-region Central as well as averaged over the entire study area. The autumn of 1959 sticks out by unusually low ADE values in all three sub-regions and thus also over the entire study area. The entire eight drought indices used within this study show pronounced drought conditions over the entire study area during autumn 1959. At the 3-month timescale of WBAI November 1959 (SON) has already been identified as driest, December 1953 (OND) as the second driest and May 2011 (MAM) as the third driest event (Table 4). These assessment based on one drought index are confirmed by the other drought indices that are integrated in ADE.

3.3.3. *Seasonal drought trends*

The maps illustrating the seasonal trends (Fig. 9) show predominantly increasing drought conditions in spring and summer and wetting trends in autumn and winter for both study periods. For the winter season there are few drying trends in the southern part of the sub-regions

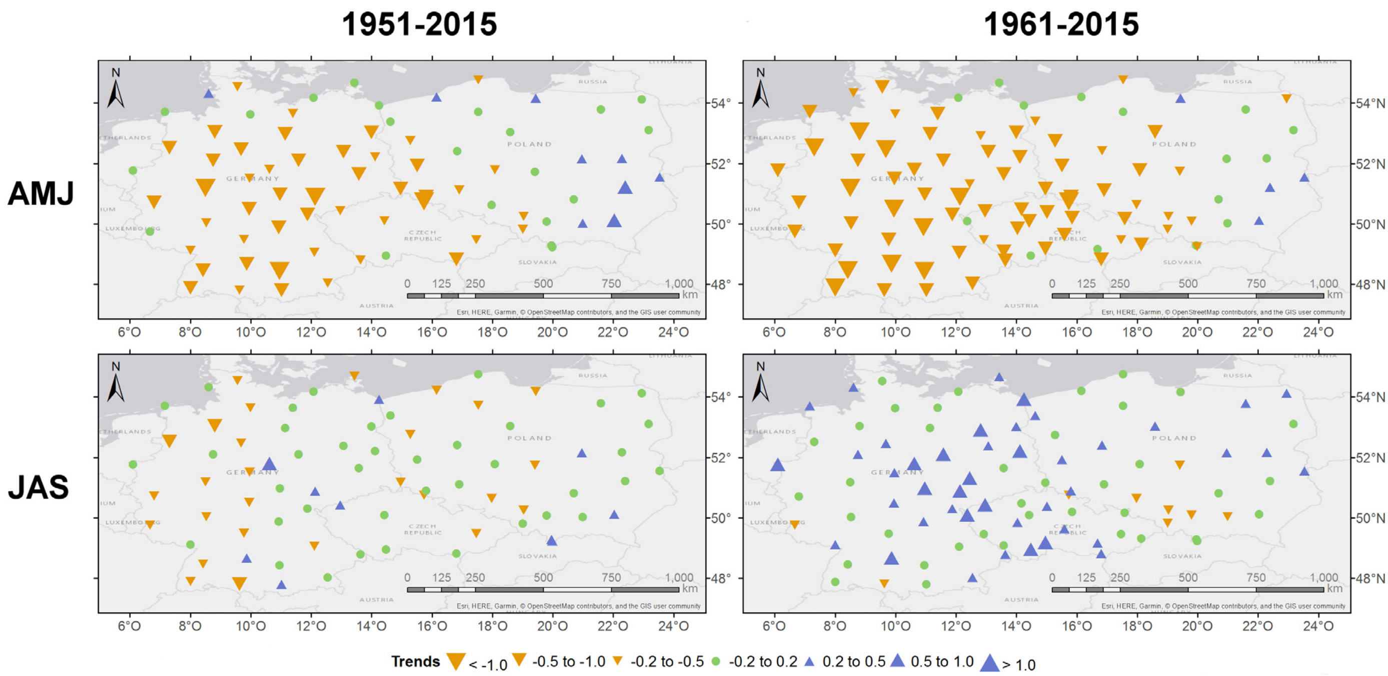


Fig. 10. ADE trends (linear regression) of the two vegetation periods comparing the periods 1951–2015 and 1961–2015.

West and East during both study periods. Trends towards drier autumns are observed in sub-region East during 1961–2015 (except for the stations in the South of this region). During the ten years longer study period these stations show slightly negative or no trends. The drying trends of spring are more pronounced during 1961–2015 than for the ten year longer period 1951–2015, which is connected to the exceptionally dry springs during the 1950s (Fig. 8). Furthermore, a West-East gradient in trend magnitude and direction is visible in spring with the most pronounced drying trends in the West (Germany) and slight wetting trends in Northern and Eastern Poland (Fig. 9). The trend towards stronger drought conditions during summer is most pronounced in sub-region West (western Germany) during 1951–2015. During this period the summer ADE trends are very small in sub-region East. The trend pattern change in the ten year shorter period 1961–2015. Here, trends towards drier conditions prevail in sub-region West and in the South of sub-region East, while the Central and Northern part of the study area show slight wetting or no trends. These differences in the trends between the two study periods are connected to wet summers in the 1950s (Fig. 8).

3.3.4. Vegetation periods

Shifting the season by one month as done by the definition of two vegetation periods shows a strong influence on the identified three driest seasons (Table 5) as well as on the trends (Figs. 6–8). Comparing the record dry years of the vegetation periods with those of spring and summer (Table 5) shows that there are only very few overlaps in the identified three driest years between VP-I (AMJ) and spring (MAM), as well as between VP-II (JAS) and summer (JJA).

The trend patterns of the two vegetation periods that are shifted by one month with respect to the spring and summer season show some similarities, but also some differences (Figs. 10 and 11). The drying trends for both study periods are amplified if the first vegetation period (AMJ) is considered instead of the spring season. For the spring season the drying trends have been dampened by the wetting trends of March as apparent in the seasonal cycle trends (Fig. 18). The West-East gradient in the trend magnitudes described for spring is also visible in the trends of the first vegetation period with the most pronounced drying trends in the West and comparatively small trends in the East of the study area (Figs. 10 and 11). Considering the second vegetation period (JAS) instead of summer delivers less frequent and less pronounced drying trends than observed for the summer season (Figs. 10 and 11). This is connected to the wetting trends during September as illustrated in Fig. 18.

3.3.5. Trend characteristics of individual drought indices

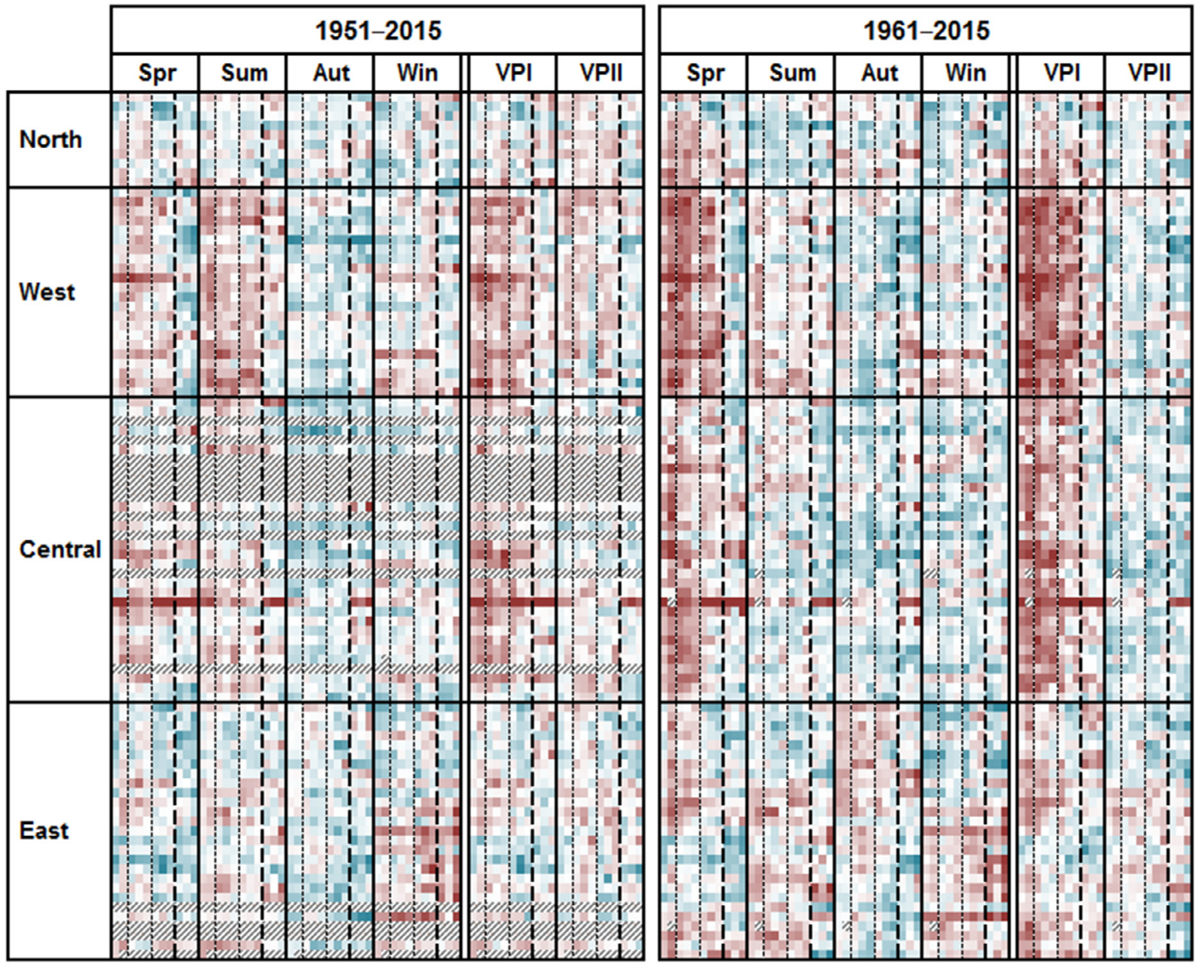
Seasonal trends for individual drought indices are described the supplementary material (Supplement 1 to Supplement 4). The Figs 11 and 12 give an overview on all computed index trends. As illustrated by the legend of Fig. 11, the different indices are arranged along the x-axis and the stations along the y-axis. A continuous color scale from blue for wetting over white (no trend) to red for drying trends is used. The scaling is done based on the values given in Table 3. Thereby, the ordering of the stations follows the one used in Table SM-1. Fig. 11 shows that magnitude and sometimes even direction of drought trends depend on the chosen index, as each index captures different characteristics of a drought event.

Fig. 12 presents a more aggregated evaluation of the trends of individual indices by displaying the percentage of stations within the seven trend classes described in Table 3. It shows that the WBAI identifies most frequently trends towards more intense drought conditions in spring, summer and the two vegetation periods. The percentage of stations with trends towards increased drought conditions in spring (and less pronounced the first vegetation period) is generally higher for indices connected with dry days than those related to low precipitation days (daily precipitation below 5 mm).

For the other seasons the differences in the percentages of stations with drought trends are less pronounced than in spring. Both Figs. 11 and 12 illustrate that the strongest drought trends over all considered drought indices, stations and study periods occur in sub-region West during the first vegetation period and during spring of period 1961–2015.

3.4. Changes in heavy precipitation

While the focus of our analysis is on drought, we included also a small selection of heavy precipitation indices (see Table 1) in our analysis. For an aggregated evaluation of heavy precipitation anomalies and



Legend:

	Station / Index	Spring mRAI	Spring WBAI	Spring DD	Spring AvD	Spring CDD	Spring LPD	Spring AvLP	Spring CLPD	Spring MxR	Spring R95pT	Spring R99pT	Summer mRAI	Summer WBAI	Summer DD	...
North	Łeba	0.1	-0.4	-0.2	-0.1	-0.3	0.2	0.2	0.1	14	15	26	-0.3	-0.5	-0.3	
	Elbląg	0.9	0.4	0.7	0.3	0.1	1.4	1.3	1.0	0.4	17	-2	0.0	-0.2	0.0	
	Koszalin	0.5	0.0	0.1	-0.2	-0.1	0.8	1.0	0.7	19	10	49	0.3	0.1	0.1	
	Świnoujście	0.3	-0.3	-0.1	-0.2	-0.5	0.1	0.2	0.3	20	12	60	0.7	0.4	0.0	
	Arkona	0.1	-0.4	0.1	-0.1	-0.3	0.2	0.1	-0.1	-7	1.3	-0	-0.2	-0.5	0.0	
	Rostock	0.0	-0.4	-0.2	-0.2	-0.5	0.3	0.5	0.4	-23	7	3.3	0.4	0.1	0.0	
	Schleswig	-0.3	-0.5	-0.1	-0.3	-0.4	0.0	-0.3	-0.2	-16	-10	-18	-0.1	-0.2	-0.2	
	Sankt Peter-Ording	0.5	0.1	0.4	-0.1	0.1	0.5	0.0	-0.2	-4	15	-1	0.6	0.4	0.2	
	Norderney	-0.2	-0.5	0.0	0.2	0.0	0.3	0.6	0.2	-13	-17	-50	0.5	0.3	-0.1	
	Schwerin	-0.2	-0.6	0.1	-0.3	-0.5	0.3	0.3	0.6	-37	-11	-71	-0.5	-0.7	0.0	
West	Hamburg-Fuhlsbüttel	0.4	0.1	-0.3	-0.5	-0.4	0.7	0.5	0.7	10	54	52	-0.2	-0.3	-0.4	
	Bremen	-0.6	-0.9	-0.8	-1.1	-0.3	-0.6	-0.8	0.0	-15	6.9	-50	-0.6	-0.7	-0.8	
	Lingen	-0.3	-0.6	-0.5	-0.3	-0.2	-0.4	-1.1	0.0	-14	10	-13	-0.8	-1.0	-0.5	
	...															

Fig. 11. Matrix of seasonal station trends (linear regression; same sequence of stations as in Table SM-1) for two monthly drought indices (mRAI and WBAI), six daily drought indices (DD, AvD, CDD, LPD, AvLP, CLPD) and three heavy precipitation indices (MxRR, R95pT, R99pT) comparing the analysis periods 1951–2015 and 1961–2015. The trend magnitude is illustrated by a color scale with blue representing trends towards wetter conditions over white (= no trend) to red representing trends towards drier conditions. Crosshatched cells indicate that no trend was computed due to insufficient data availability (more than 10% missing values). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

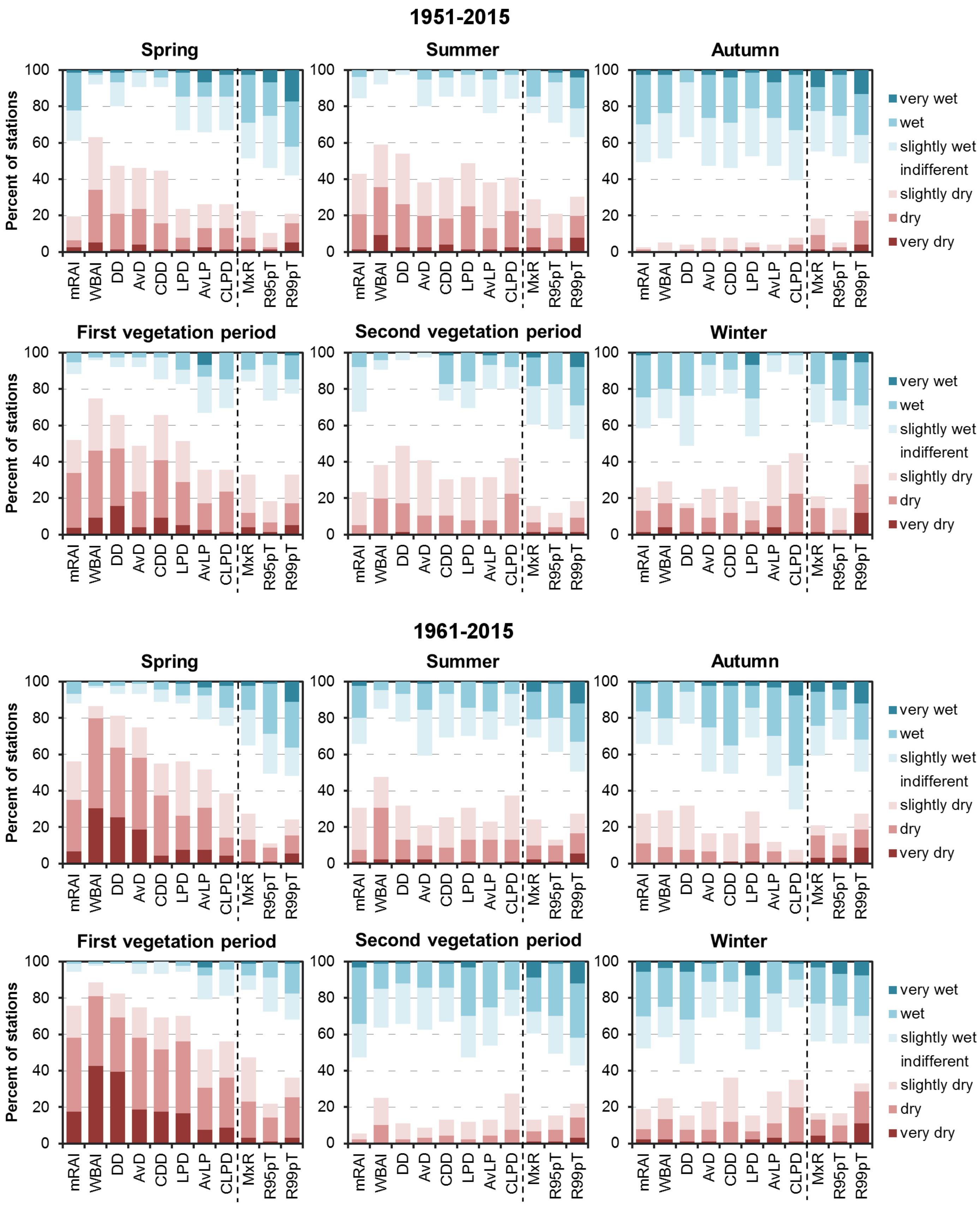


Fig. 12. Spatial trend homogeneity illustrated by the percentage of stations with positive and negative trends (in 7 categories; see Table 3) for 11 indices (see Table 1) for the seasons and vegetation periods comparing the periods 1951–2015 and 1961–2015.

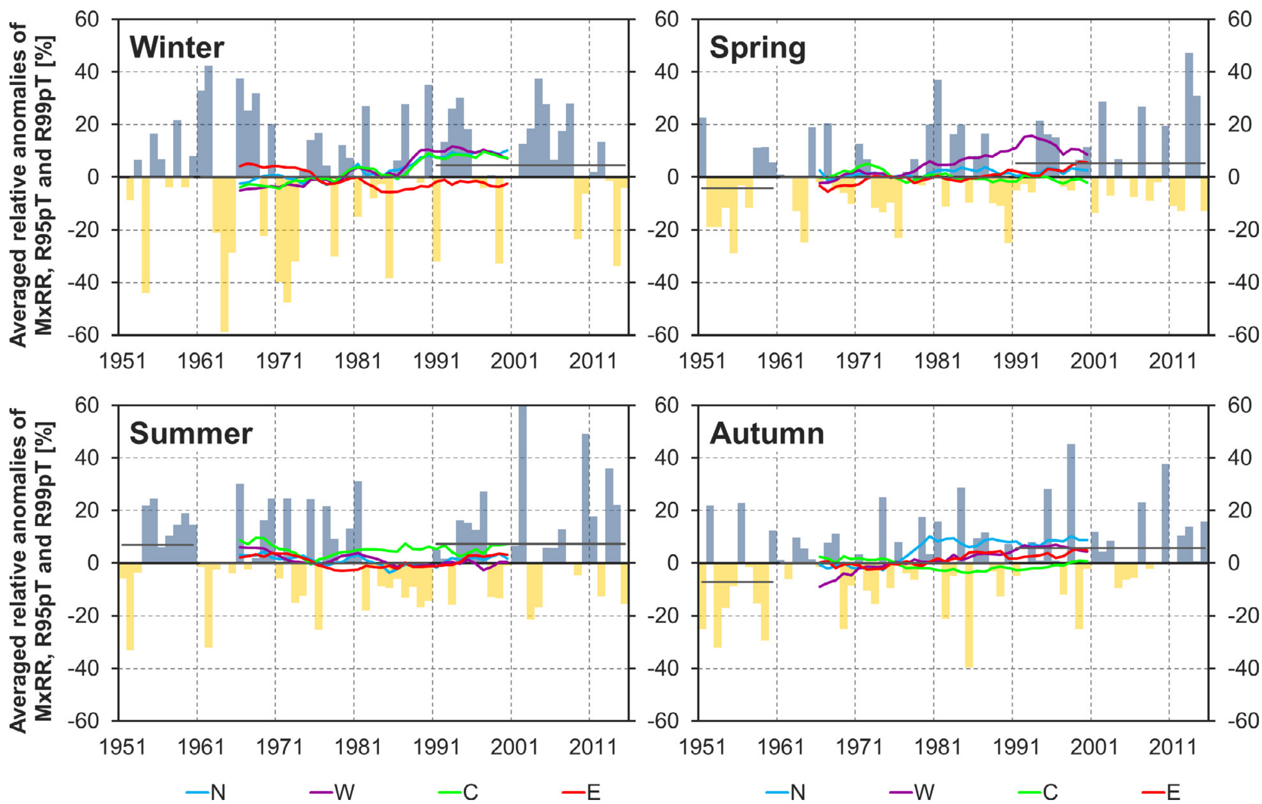


Fig. 13. Seasonal time series of the regionally averaged relative anomalies of three heavy precipitation indices (MxRR, R95pT and R99pT). The grey lines indicate the averaged anomalies of 1951–1960, 1961–1990 and 1991–2015. The anomalies for the four sub-regions are displayed as 31-year moving averages.

trends the indices were expressed as relative anomalies from the normal conditions of 1961–1990. In the following figures and in Table 6 the regional average of the mean anomaly of MxRR, R95pT and R99pT (this average is furthermore abbreviated as AHP) as well as the respective trends are displayed and interpreted. Specific seasonal assessments for the index R99pT are presented in the supplementary material (Supplement 1 to Supplement 4). The display of station trends for all three heavy precipitation indices in Figs. 11 and 12 allows for a direct comparison between drought and heavy precipitation trends in individual seasons.

Fig. 13 presents the seasonal AHP time series. In all seasons the average of 1991–2015 is higher than the one of 1961–1990, indicating an increase in heavy precipitation in recent decades. In winter this increase is obvious in all sub-regions except for the Eastern part of the study area. During spring the strongest positive deviation from normal conditions in recent decades occurs in sub-region West, while those during summer are highest sub-region Central and those during Autumn in the sub-regions North and East. The spring (2013) and the summer (2002) with the most pronounced positive heavy precipitation anomaly occurred both in the 21st century. Table 6 gives an overview on the three wettest years according to AHP for each season and the two vegetation periods. The winters with most pronounced heavy precipitation events occurred in 1962, 1966 and 2004. All three summers with the most extreme precipitation occurred in the 21st century, namely 2002, 2010 and 2013. Spring seasons with exceptionally pronounced heavy precipitation have been 2013, 1981 and 2014, while the three most extreme autumns occurred in 1998, 2010 and 1984. The record years of heavy precipitation for individual sub-regions show less similarities to those described for the entire study area as compared to the Aggregated Drought Evaluation presented in Table 5. This indicates that heavy precipitation events are spatially less extended than drought events leading to more distinctive differences in the characteristics of the sub-regions.

In all seasons stations with increasing AHP-trends prevail over those showing decreases (Fig. 14). Generally, the AHP trends (Fig. 14) are spatially more variable than the ADE trends (Fig. 9) with neighboring stations showing opposite trends. The two study periods generally don't show as spatially consistent differences in trend magnitude and direction of heavy precipitation as described for the drought indices. Just during summer there are considerably more and higher increasing AHP-trends in sub-region Central for the shorter period 1961–2015 as compared to 1951–2015. For the second vegetation period (JAS) this pattern of increasing AHP trends in period 1961–2015 stretches even more to the West (Fig. 15). The first vegetation period (AMJ) shows considerably less increasing heavy precipitation trends during both study periods than observed for spring, indicating that the positive AHP-trends of spring are probably connected to the precipitation increases in March (Fig. 18b).

3.5. *Temporal stability of trends*

The comparison of the trends of the two study periods of 55 and 65 years duration already showed distinct differences in trend magnitude and direction, indicating that the times series are a bit short for a robust identification of long-term trends in drought and heavy precipitation over Central Europe. A moving 30-year trend analysis was performed for each season in order to assess the temporal stability of drought (Fig. 16) and heavy precipitation (Fig. 17) trends. During all seasons the regionally averaged 30-year trends alternate between positive and negative ones showing the trends of no season are stable over time, due to the pronounced (multi)decadal variability of precipitation. But for each season one trend direction is prevailing leading to the respective long-term trends described in Sections 3.3 and 3.4. More 30-year trends indicate increasing drought conditions in spring and summer, while in autumn and winter the majority of trends point towards decreasing drought conditions (Fig. 16). 30-year trends towards increasing heavy precipitation prevail in autumn, winter and spring. For the summer season slightly

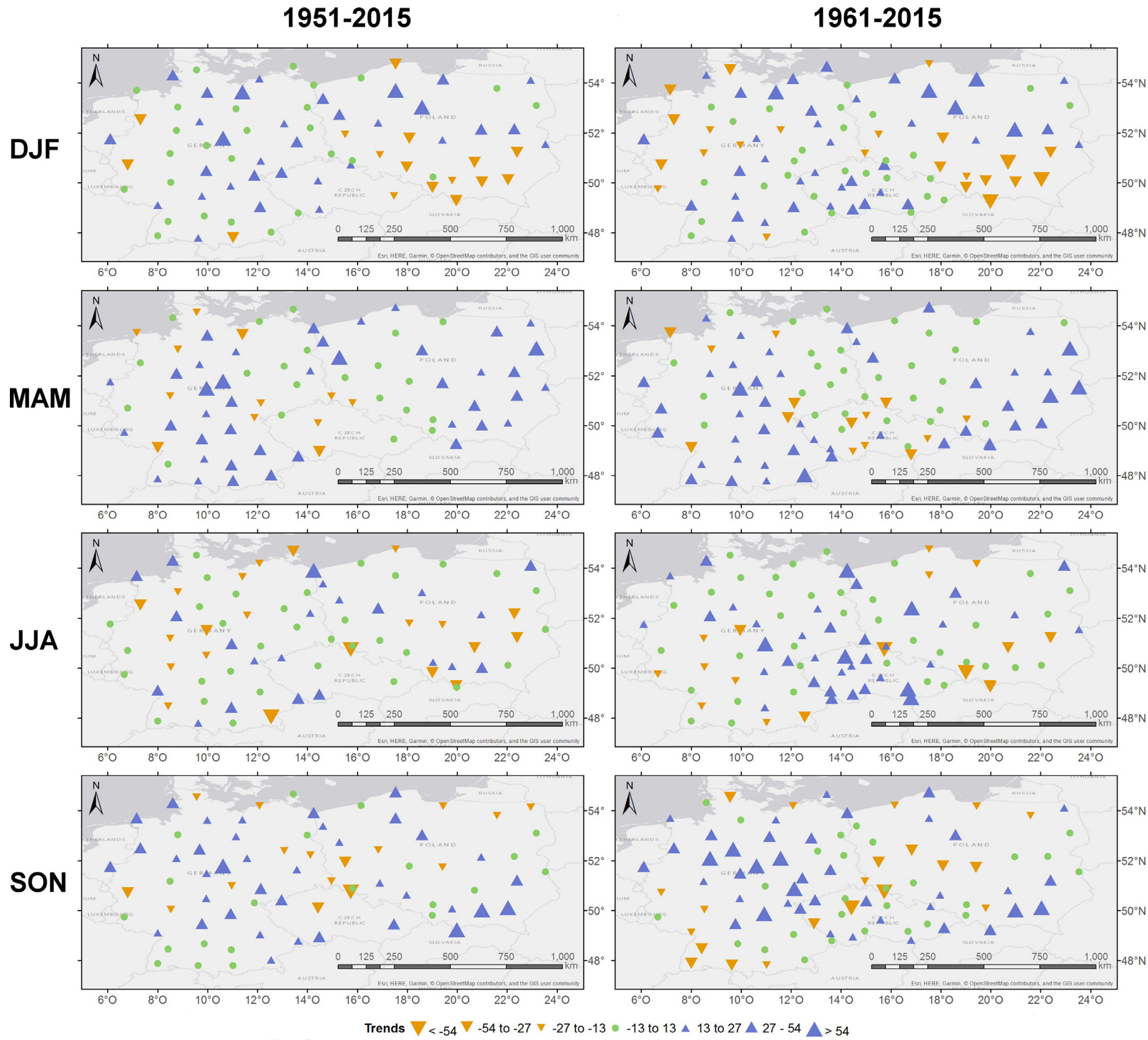


Fig. 14. Seasonal trends (linear regression) of AHP (averaged anomalies of the heavy precipitation indices MxRR, R95pT and R99pT) comparing the periods 1951–2015 and 1961–2015.

more negative than positive AHP-trends occur, but since 1973–2002 the regionally averaged trends have been consistently positive indicating increasing heavy precipitation in recent years. The same development, but less pronounced and a bit later (since 1981–2010) has been observed for the ADE summer trends.

Although there are sometimes distinct differences in the trend magnitude of the sub-regions there are similarities in the ups and downs of the regional averages particularly for the drought trends (without display). For the heavy precipitation trends there are much less similarities in the course of the sub-regional trend time series, indicating the lower spatial coverage of heavy precipitation events in comparison to drought.

3.6. Seasonal cycle – characteristics and trends

Changes in the seasonal cycle of temperature, precipitation and water balance are studied as a basis for evaluating the seasonal drought trends of different drought indices. The seasonal cycles of temperature and precipitation (Fig. 18) show the typical characteristics of a temperate climate on the Northern hemisphere with average winter temperatures below zero, average summer temperatures above 15 °C and precipitation throughout the entire year. The climatic water balance is positive during the winter half year, while there is on average a water deficit between April and September.

Within period 1951–2015 average temperature increased in the study area during all months by on average 1.6 K (0.6–2.7 K), with the lowest increases during June and the autumn months. The spatial variability of the temperature trends as depicted by the standard deviation of station trends within Fig. 18 and by the regionally averaged trends in Fig. 19 is quite low. Precipitation trends show a much larger variability during the course of the year and also a much higher spatial variability of trend values. Decreasing precipitation trends for period 1951–2015 mainly occur during April, June to August and end of November, while the strongest precipitation increases were observed for March, June and September.

Table 6
Three wettest years per season and sub-region with the strongest averaged anomaly of heavy precipitation indices (AHP: relative anomalies in percent of MxRR, R95pT and R99pT).

Season	Rank	Study area AHP [%]	Study area Year	North Coast AHP [%]	North Coast Year	West AHP [%]	West Year	Central AHP [%]	Central Year	East AHP [%]	East Year
Winter	1	48.5	1962	86.0	1966	73.2	1990	61.4	2005	64.2	2006
	2	37.6	1966	78.9	1990	67.2	1962	60.6	2003	61.1	1977
	3	37.4	2004	69.4	2015	57.8	1958	57.5	1987	58.3	1960
Spring	1	47.4	2013	83.4	1951	71.1	2013	39.0	1980	58.1	2010
	2	37.1	1981	61.5	1996	71.1	1981	37.5	2007	55.7	2014
	3	31.0	2014	48.1	2010	70.9	2007	34.5	1959	48.7	2013
Summer	1	66.0	2002	68.9	1969	58.8	2002	95.6	2002	67.2	2010
	2	49.2	2010	54.9	2011	52.1	1994	65.9	2013	64.2	1997
	3	36.1	2013	45.3	1960	47.7	1981	55.4	1977	59.5	1970
Autumn	1	45.4	1998	69.4	1995	71.4	1998	56.2	2010	62.8	1974
	2	37.6	2010	67.1	1993	58.5	1984	47.6	1998	59.4	1952
	3	28.8	1984	65.7	1994	55.7	1986	43.0	1979	54.0	1995
VP-I	1	68.7	2013	79.6	1980	72.0	1981	96.8	2013	44.1	2010
	2	35.0	2007	60.9	1984	68.6	2007	37.8	2007	40.7	2013
	3	26.7	1980	58.2	2013	66.9	2013	35.5	1971	40.1	1966
VP-II	1	64.1	2002	59.6	2011	58.8	2002	92.4	2002	77.5	1997
	2	58.1	2010	55.4	1995	51.7	1956	66.7	1959	72.1	2010
	3	35.0	1997	50.2	1960	50.3	2010	60.1	1981	56.1	1970

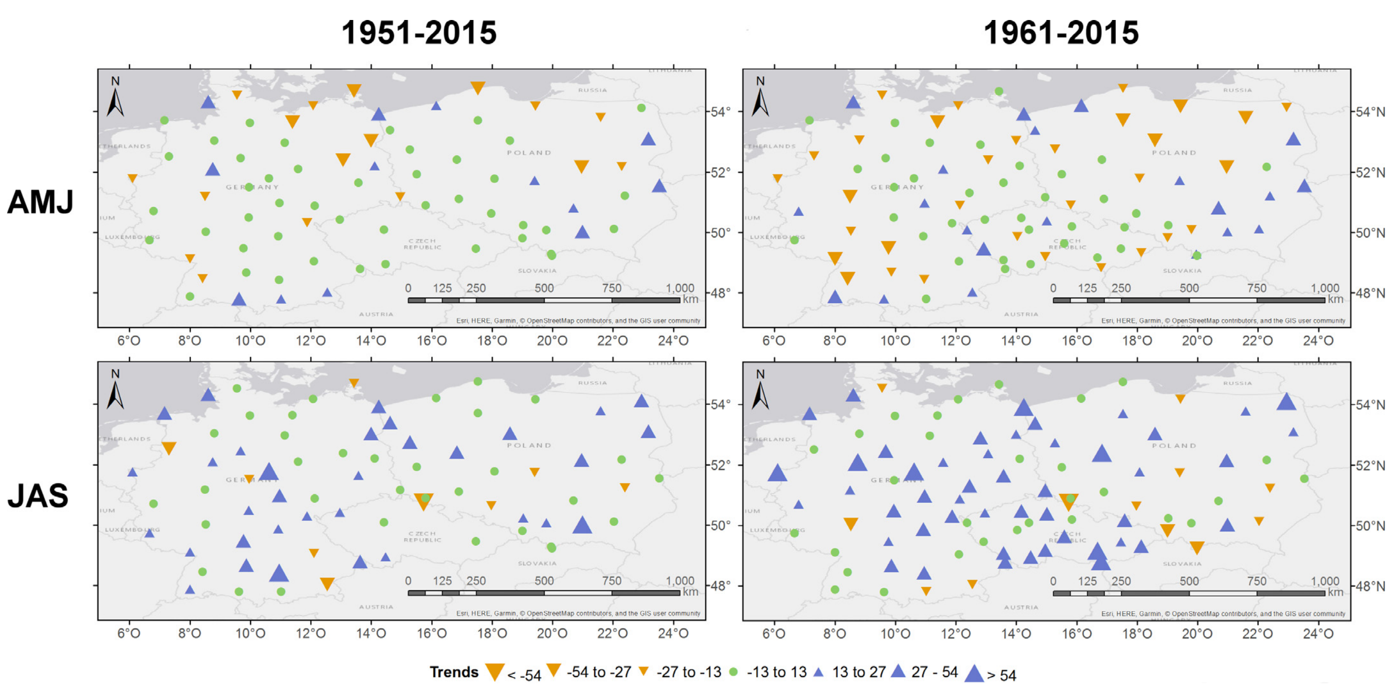


Fig. 15. AHP-trends (linear regression) for the two vegetation periods (VP-I: AMJ; VP-II: JAS) comparing the study periods 1951–2015 and 1961–2015.

The trend directions of the climatic water balance are similar to those of precipitation, but due to the temperature increases there are more frequent and more pronounced negative water balance trends compared to negative precipitation trends. The most pronounced negative trends are observed for April and July to August leading to an intensification of the naturally occurring water deficit during those months. A distinct increase in water balance is only observed in September, the month with a comparatively low temperature increase and the most pronounced precipitation increase. The described differences in the trend direction and magnitude for adjacent months may lead to inconclusive seasonal or annual trends.

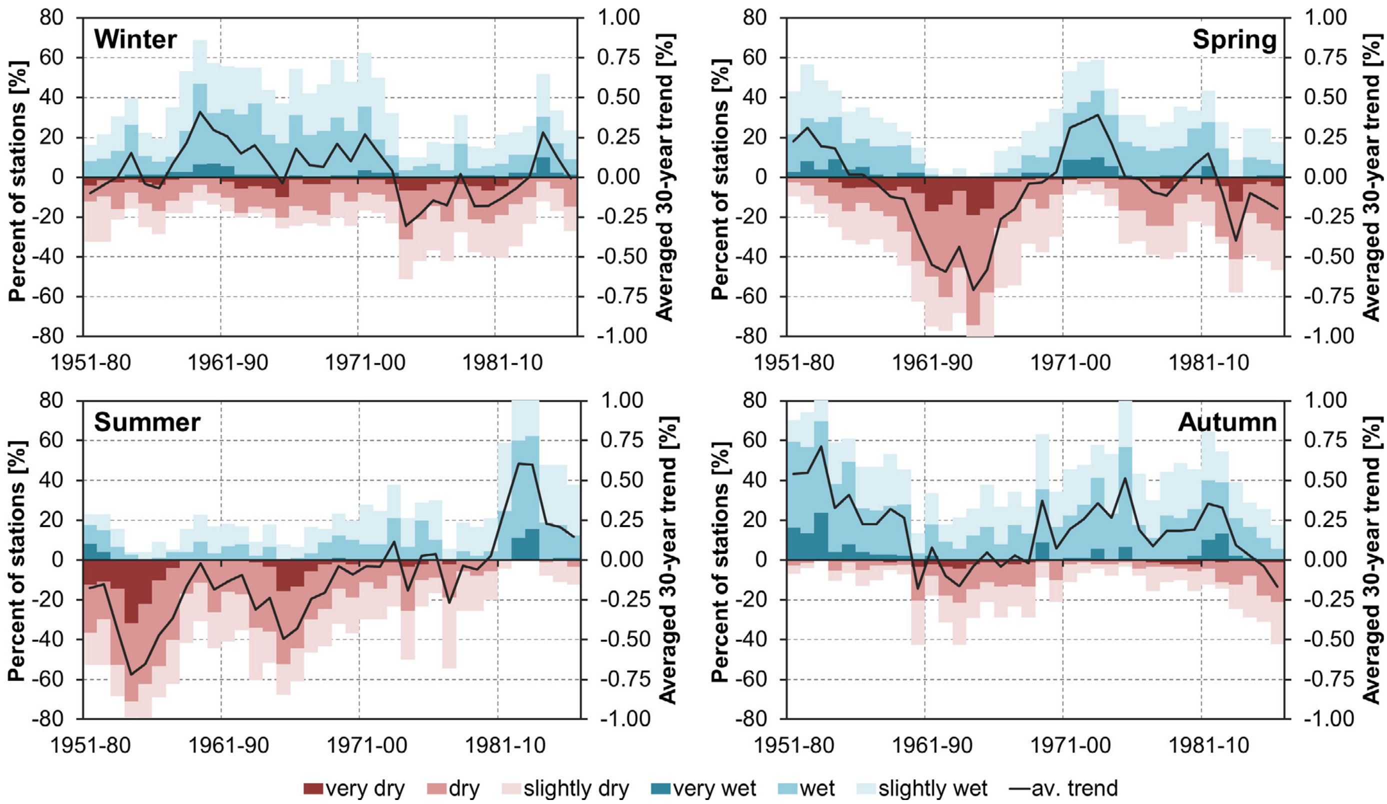


Fig. 16. Display of 30-year trends of ADE starting from 1951–1980 till 1986–2015 for the entire study area.

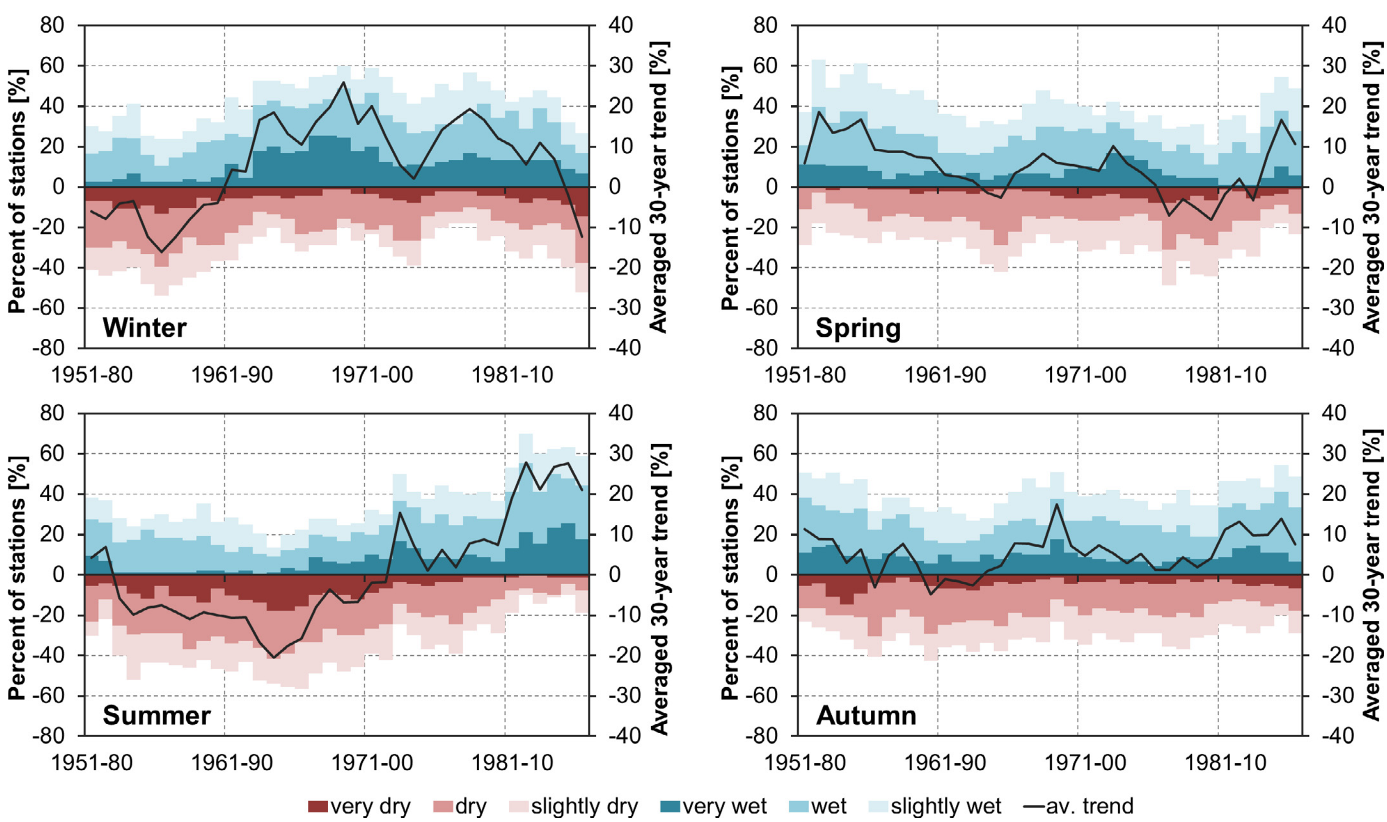


Fig. 17. Display of 30-year trends of the averaged heavy precipitation index anomalies starting from 1951–1980 till 1986–2015 for the entire study area.

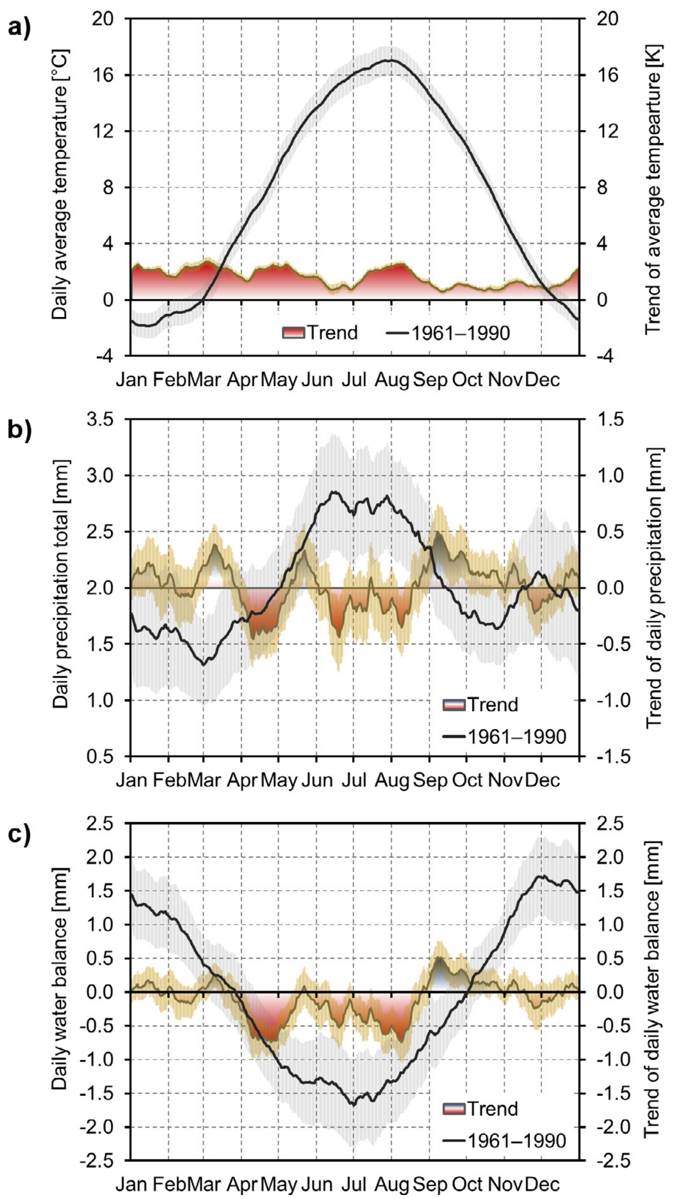


Fig. 18. Seasonal cycle of (a) average daily temperature, (b) daily rainfall totals, and (c) daily water balance. The black line is the average for 1961–1990 and the grey band the spatial standard deviation. Additionally displayed are the daily linear trends for 1951–2015 (31-day moving average) together with the spatial standard deviation of trend values (brown band).

Fig. 19 gives a first impression of the temporal trend stability by comparing the regionally averaged trends of the periods 1961–2015 and 1951–2015. Generally, the intra-annual differences are larger for the 10 year shorter period 1961–2015. This indicates that such seasonal trend differences are likely influenced by chance even for periods longer than 50 years and thus should not be overinterpreted. Nonetheless, the comparatively strong temperature increases during April to May, July to August and December to January are visible for both study periods as well as for the daily minimum and maximum temperature.

With respect to drought conditions, the decrease in precipitation and water balance in April is the temporally and spatially most stable trend signal. Comparing the trends of the four sub-regions (Fig. 19) shows that first the regional variability of temperature trends is lower than the one of trends related to precipitation and second there is an East-West gradient in trend magnitude during many times of the year. Sometimes, also the coastal areas in the North of the study area show trend values most different from the other regions.

4. Discussion

While many drought studies focus on long-term accumulation periods without taking into account the seasonality of droughts, we have analyzed the seasonal and regional drought pattern within Central Europe (Germany, Poland, Czech Republic) using eight drought indices, encompassing mRAI (similar to SPI), WBAI (similar to SPEI), dry period indices based on the thresholds of 1 mm/day and 5 mm/day. Changes in the seasonal timing of drought are important for dealing with drought impacts and taking management decisions.

Based on the aggregated evaluation of eight drought indices the TOP3 of the driest seasons were identified (spring: 2011, 1953, 1976; summer: 1976, 1982, 2003; autumn: 1959, 1953, 2011; winter: 1963/64, 1971/72, 2013/14). Additionally the seasons with the most pronounced heavy precipitation were identified using three heavy precipitation indices (spring: 2013, 1981, 2014; summer: 2002, 2010, 2013; autumn: 1998, 2010, 1984; winter: 1961/62, 1965/66, 2003/04). An accumulation of the seasonal TOP3 in recent decades is observed for the studied heavy precipitation indices in spring, summer and autumn and also under the TOP3 drought seasons is always a year of the beginning of the 21st Century, indicating that drought and heavy precipitation are relevant hazards in recent times in Central Europe.

The study of changes in the drought conditions within 1951–2015 shows that trends towards drier conditions are prevailing in spring and less pronounced in summer, while the autumn and to a lesser extent the winter months show mainly trends towards wetter conditions. This fits the results obtained by other studies. For instance Spinoni et al. (2017) describe increases in drought severity and frequency during spring (1950–2015) and summer (1950–2014) based on the SPEI and unclear trends based on SPI. For autumn and winter their study presents decreasing trends in drought frequency and severity during 1950–2014 based on the SPI and indifferent SPEI trends. Spinoni et al. (2018) obtain similar seasonal drought frequency trends for 1951–2010 based on an combined drought indicator integrating SPI, SPEI and the Reconnaissance Drought Index RDI (Tsakiris and Vangelis, 2005) with an increasing drought frequency in spring, moderate increases in summer and mixed tendencies in autumn and winter. For Central Eastern Poland Radzka (2015) described increasing drought conditions for the vegetation period (AMJJAS) within period 1971–2005.

With regard to the temporal stability of trends we found similarities in the general spatial trend patterns for 1951–2015 and the 10 year shorter period 1961–2015, but there are also some distinct dependencies of trend magnitude and sometimes direction on the study period. Spinoni et al. (2017) also describe dependencies of the trend direction on the study period and the influence of individual drought events at the beginning and the end of the study period on the computed trends. For 1981–2014/15 they describe increases in drought frequency also for the SPI, while the summer trends of SPEI are now indifferent and the winter trends increasing. The analysis of moving 30-year trends showed restricting in the relevance of linear trends due to pronounced multi-decadal variations in precipitation and drought characteristics. For instance, Haslinger and Bloschl (2017) describe multidecadal variations of drought frequency, duration, intensity, and severity for the Greater Alpine Region within period 1780 and 2014, but no consistent trends. Particularly dry or wet decades at the beginning or the end of the study period strongly influence the results of trend analyses. Generally, the drought trends for 1961–2015 are more pronounced than those for 1951–2015 as the 1950s have been a very dry decade in Europe (Briffa et al., 1994; Lloyd-Hughes and Saunders, 2002; Van der Schrier et al., 2006).

The trends not only depend on the study period, but also on the season definition, as the comparison of spring (MAM) and VP-I (AMJ) as

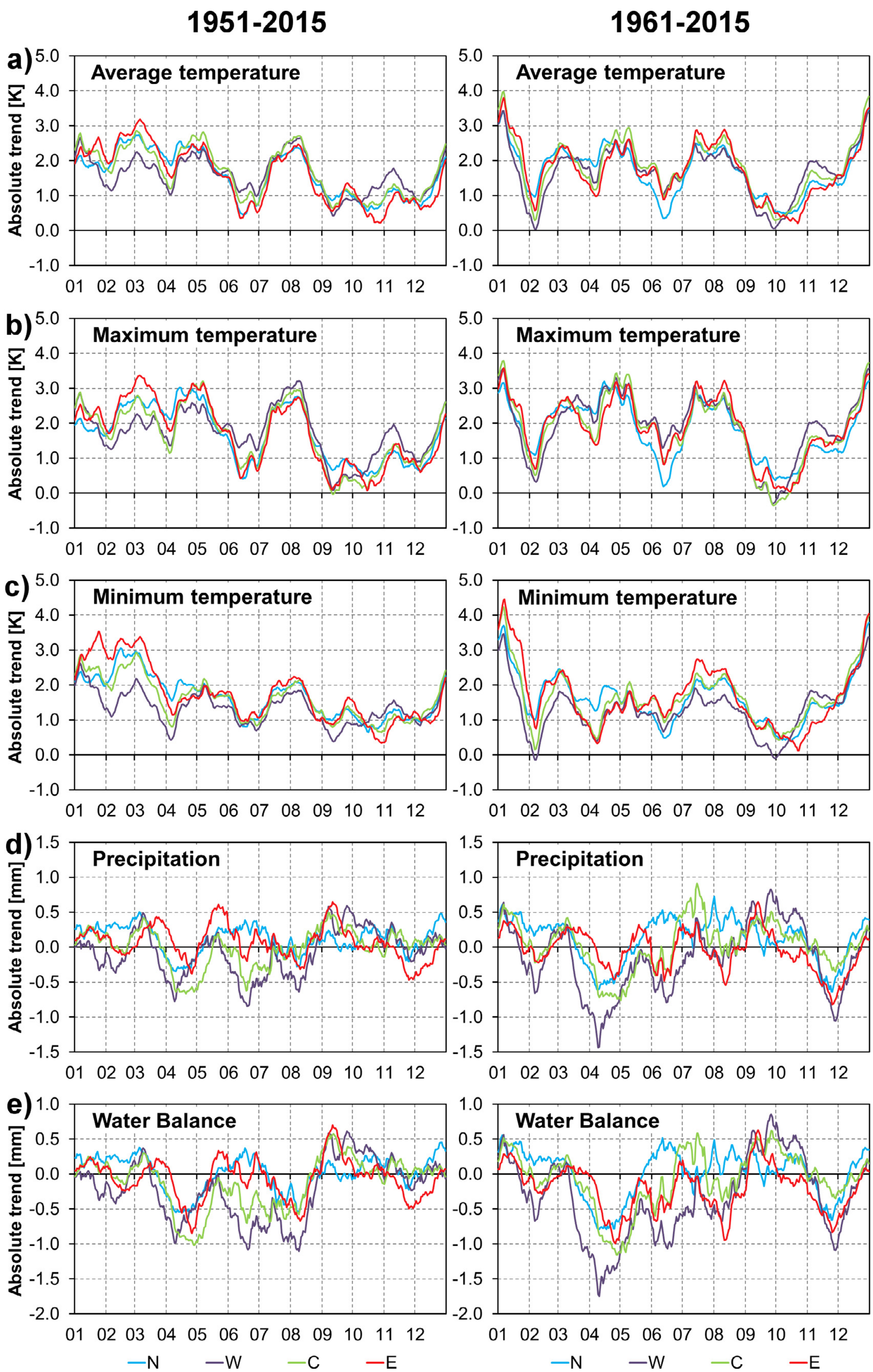


Fig. 19. Regional averages of daily linear trends (31 day moving average) for (a) average temperature, (b) maximum temperature, (c) minimum temperature, (d) precipitation total and (e) water balance for the periods 1951–2015 (left panels) and 1961–2015 (right panels).

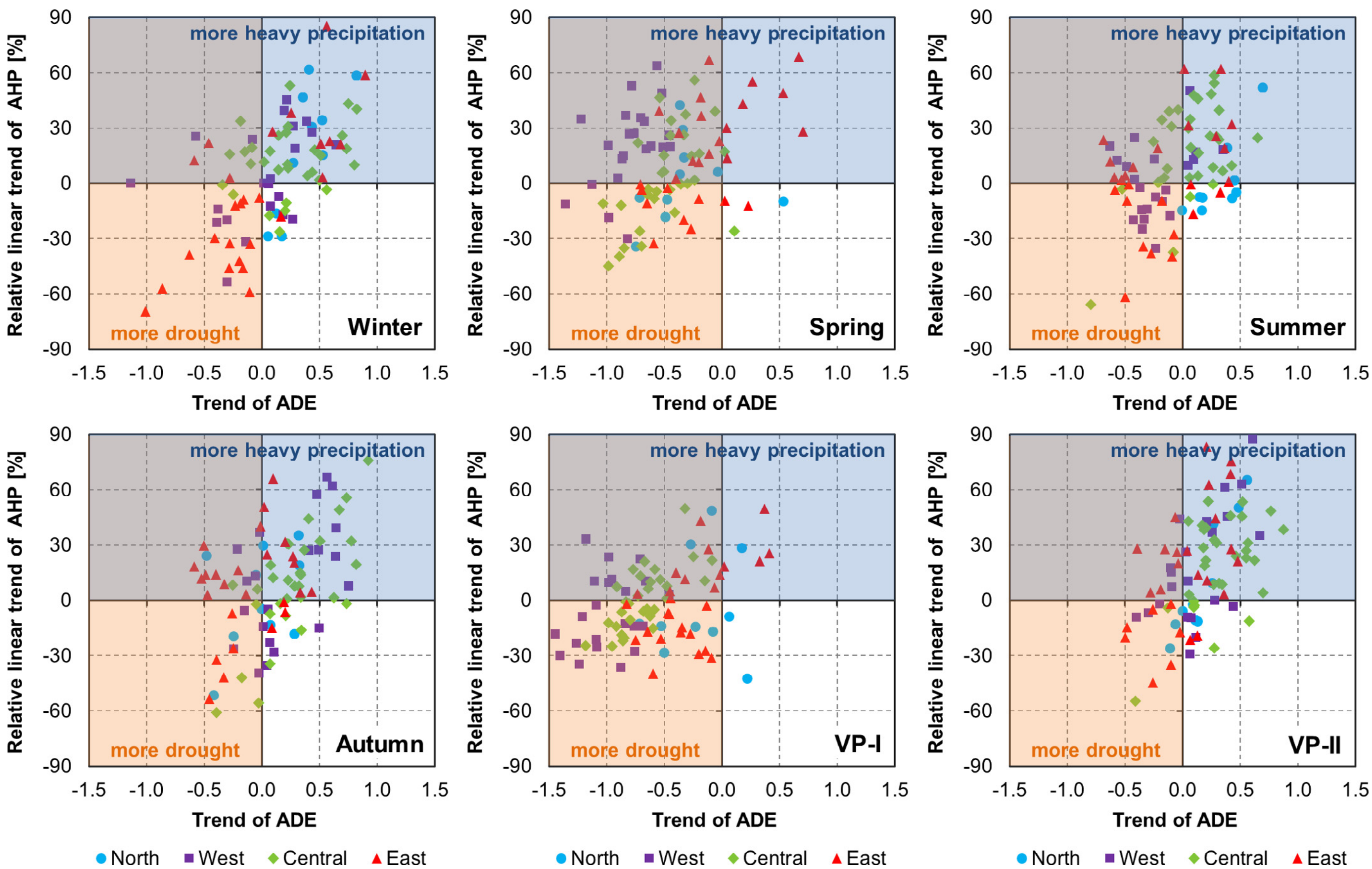


Fig. 20. Comparison of the Aggregated Drought Evaluation (ADE) and Averaged Heavy Precipitation (AHP) station trends for the seasons and vegetation periods for study period 1961–2010. The regional classification of the stations is indicated by different colors of the symbols. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

well as summer (JJA) and VP-II (JAS) shows. The analysis of smoothed daily trends show the strongest drought trends during April and within the regions West and Central also in June, leading to more pronounced drought trends of VP-I in comparison to spring. Furthermore, the study of daily precipitation and water balance trends over the seasonal cycle shows a wetting trend in March and September. This coincides with more drying trends in summer as compared to VP-II. The larger temperature increases from mid-July to mid-August in comparison to June lead to an intensification of drought trends of WBAI during this period. For instance, the WBAI trends of July/August for region West reach a similar magnitude like those within June, despite less pronounced precipitation decreases. The analysis of daily trends within the seasonal cycle shows that with permanently defined seasons the identification of the strongest drying during the seasonal cycle is not possible.

The trends towards pronounced drought conditions in spring and summer do not exclude trends toward more frequent heavy precipitation events, but often different stations and regions, respectively, are contributing most to these regional trends. Fig. 20 shows for each station the magnitude of drought (ADE index) in comparison to heavy precipitation (AHP) trends of period 1961–2015.

Generally, there is a more or less pronounced correlation between the drought and heavy precipitation trends (Fig. 20). Stations showing a strong drying trend have on average a negative or at least a smaller positive heavy precipitation trend than those with a wetting trend. In spring and VP-I this relationship between ADE and AHP trends is shifted towards drying trends, so that there are more stations with simultaneous trends towards more drought and more heavy precipitation than in the other seasons. This is particularly pronounced for region west during spring, where all stations show drying trends and the majority at the same time also an increase in heavy precipitation. These simultaneous trends of increase drought conditions and heavy precipitation events still may refer to different months within the season showing more distinct changes than the other months of the season. The possible relation of the West-East gradient in drought trends observed in spring to the gradient in continentality over the study area and changing circulation pattern, respectively, needs to be studied further.

High temperatures, particularly during the warm part of the year, lead to higher evapotranspiration rates. Such increased PET rates lead to a drying of soils and enhanced sensible heat fluxes that for their part again lead to higher temperatures and evapotranspiration rates, respectively. Furthermore, increased PET rates not only intensify drying in areas with decreasing precipitation trends, but may also drive areas into drought than experience no changes in precipitation or even show slight precipitation increases (Cook et al., 2014; Dai, 2011). Briffa et al. (2009) describe that increasing temperatures have a major influence on the trend toward drier summer conditions, particularly in central Europe. Several other studies including process oriented studies like from Träger-Chatterjee et al. (2013) and such on future climate projections as the one by Cook et al. (2014) have demonstrated the importance of including temperature in the drought assessment in a warming climate. Hanel et al. (2018) argue that recent seasonal drought over Europe were generated by different physical processes than their historical long-term counterparts. They are often initiated during the vegetation period, while the most extreme drought events during the last 250 years, which were longer, more intense and spatially more extended than the recent events were initiated during late summer/ early autumn.

5. Conclusions

The observed trend towards drier springs and summers is of high relevance for agriculture and forestry, but also for water management (e.g. reservoir management) or shipping. As the most recent example of 2018 has shown droughts in Central Europe come along with strong harvest shortfalls for many crops, dying of trees particularly in young plantations, more frequent forest fires, restrictions in inland water transportation and water limitations for some activities in industry and energy production. With regard to drought impacts also the interaction of precipitation deficits with extreme temperatures and drying soils is of vital importance, as the impact resulting from combined heat and drought extremes are more severe than those of individual extremes (Hegerl et al., 2011). The present study of seasonal drought trends over Central Europe showed the relevance of rising average earth surface temperature and related increases in potential evapotranspiration for the severity of recent drought events, particularly during the warm season. Thus, the inclusion of temperature and accordingly evapotranspiration in the calculation of drought indices is of high relevance for a reliable assessment of drought impacts in recent and future decades.

Despite the regionally averaged trends towards increasing drought conditions in spring and summer there are at the same time increasing trends of heavy precipitation related indices. This indicates that during these seasons the precipitation characteristics may get more extreme at both sides of the probability distribution, meaning that we have to expect more severe droughts and more extreme heavy precipitation and related flash flood and river flooding at the same time. These simultaneous regionally averaged seasonal trends towards increasing drought and heavy precipitation are often related to different stations/sub-regions and/or months. Generally, climate model simulations project a continuation of these trends over Central Europe within the 21st century (Huang et al., 2015; Osuch et al., 2016; Potopová et al., 2018; Rajczak and Schar, 2017; Ruosteenoja et al., 2018; Schwarzak et al., 2015) leading to the conclusion that climate adaptation measures are needed for both droughts and floods. Further studies on the relation of drought trends with changes in atmospheric circulation could help to explain the observed West-East-gradient in drought trends.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.advwatres.2019.03.005.

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